REVIEW OF FUSION SYSTEMS AND CONTRIBUTING TECHNOLOGIES FOR SIHS

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Abstract

The major objectives of the report were to identify and review the field of image fusion and contributing technologies and to recommend systems, algorithms and metrics for the proposed SIHS TD Vision SST fusion test bed. A search of the relevant literature was conducted using the relevant databases and approximately 150 papers of primary utility were identified for review. The report provides an in-depth introduction to fusion hardware and software technologies and evaluation metrics. The effort focused on identifying promising sensing fusion technologies that could be utilized by the Soldier's Integrated Helmet System Technology Demonstrator (SIHS TD). The SIHS TD Vision Sub-System Team plans to develop a fusion test bed in the near term to quantify dismounted soldier performance. The systems examined in this project were projected to be mature and compatible with man packed applications by the year 2007. The literature review identified considerable technological advancements in sensor size reduction, power demand reductions, and increases in resolution. The report analysed select sensor systems for their suitability in the fusion test bed based on sensor form factors, detector resolution, and real time performance. Recommendations on what sensors to include in the fusion test bed are included. The report provides an in-depth introduction into image fusion approaches. A list of potential fusion algorithms were identified and reviewed. Recommendations on what fusion algorithms should be examined in the fusion test bed are provided. A number of subjective and objective fusion evaluation approaches and metrics were proposed in the literature to quantify and qualify image fusion performance. Recommendations on what valid fusion metrics should be utilized in the fusion test bed are provided. Improvements to fusion subjective evaluation approaches are also detailed. Finally, summary suggestions for the Vision SST fusion test bed are provided.

Résumé

Le rapport a principalement pour objectifs de déterminer et d'examiner le domaine de la fusion d'images et des technologies d'appui, ainsi que de recommander des systèmes, des algorithmes et des mesures pour le banc d'essai de fusion de l'équipe des sous-systèmes de vision, dans le cadre de la démonstration de technologie - casque intégré pour soldat (DT - SIHS). Une recherche de la documentation pertinente effectuée dans les bases de données appropriées a permis de trouver environ 150 documents d'utilité immédiate pour l'examen. Le rapport présente en détail les technologies et les mesures d'évaluation du matériel et du logiciel de fusion. Les travaux visent essentiellement à déterminer les technologies prometteuses de fusion et détection, qui pourraient être utilisées dans le cadre de la DT - SIHS.

L'équipe des sous-systèmes de vision de la DT - SIHS planifie le développement à court terme d'un banc d'essai de fusion permettant de quantifier le rendement des soldats débarqués. Les systèmes examinés dans le cadre de ce projet devraient être au point et compatibles avec les applications portatives d'ici 2007. L'examen de la documentation a fait ressortir des progrès technologiques considérables en matière de réduction de la taille des capteurs, de réduction de la puissance consommée et d'augmentation de la résolution. Le rapport analyse des systèmes de capteurs sélectionnés pour établir leur adaptabilité au banc d'essai de fusion en fonction des facteurs de forme des capteurs, de la résolution des détecteurs et du rendement en temps réel. Des recommandations sont incluses quant aux capteurs à intégrer au banc d'essai de fusion. Le rapport présente en détail des méthodes de fusion d'images. Une liste des algorithmes de fusion possibles est dressée et examinée. Des recommandations portent sur les algorithmes de fusion qu'il y a lieu d'examiner pour le banc d'essai de fusion. Un certain nombre de méthodes et de mesures d'évaluation subjective et objective de la fusion sont proposées dans la documentation en vue de la quantification et de la qualification du rendement de fusion d'images. Des mesures de fusion valides sont recommandées pour le banc d'essai de fusion. Des détails sont également fournis sur les améliorations qu'il y a lieu d'apporter aux méthodes d'évaluation subjective de la fusion. Enfin, des suggestions sommaires sont présentées pour le banc d'essai de fusion de l'équipe des sous-systèmes de vision.

Executive Summary

The major objectives of the report were to identify and review the field of image fusion and contributing technologies and to recommend systems, algorithms and metrics for the proposed SIHS TD Vision SST fusion test bed.

A search of the relevant literature was conducted using the following databases: PsycInfo, National Technical Information Service (NTIS), SPIE, IEEE, Optical Engineering, GlobalSpec, Defence Research Reports and the World Wide Web (www). Keywords included combinations of "Image Fusion" and "Sensor", "Hardware" and "Multi-sensor". When a keyword yielded an unmanageable (too many) number of references, the researcher systematically added additional keywords to refine the search. In general, this process produced many irrelevant references. "Snowball" techniques starting with known authors and papers and following up their references to other work tended to produce more fruitful results. At the end of the search, approximately 150 papers of primary utility were identified for review.

The report provides an in-depth introduction to fusion hardware and software technologies and evaluation metrics. Factors affecting performance are introduced. The review also identified development trends for various existing and emerging sensor technologies, fusion approaches and evaluation metrics. The effort focused on identifying promising sensing fusion technologies that could be utilized by the Soldier's Integrated Helmet System Technology Demonstrator (SIHS TD). The SIHS TD Vision Sub-System Team plans to develop a fusion test bed in the near term to quantify dismounted soldier performance. The systems examined in this project were projected to be mature and compatible with man packed applications by the year 2007.

Over 200 potential SIHS TD imaging sensors were identified in this review. The sensors included the following:

- Night cameras
    - LLLTV
    - ICCD
    - ICMOS
    - EMCCD
    - EBCMOS
    - CCD/CMOS Hybrid
    - Colour CMOS
- Thermal Sensors
    - Thermal Light Valve (TLV) CMOS Camera
    - SWIR
    - MWIR/LWIR
    - Fused SWIR & LWIR

The literature review identified considerable technological advancements in sensor size reduction, power demand reductions, and increases in resolution. A new thermal imaging system based upon a passive optical filter called a thermal light valve may provide significant benefits to future soldier modernization programs. Advances in the resolution of ICMOS and EBCMOS low light cameras may eliminate the need to incorporate image intensified NVGs on future helmets. The report

analysed select sensor systems for their suitability in the fusion test bed based on sensor form factors, detector resolution, and real time performance. Recommendations on what sensors to include in the fusion test bed are included.

The literature review also identified COTS fusion boards that could accelerate the SIHS TD Vision Sub-System Team's fusion test bed development. State of the art fusion processing system architectures are described. The report analyses selected fusion systems based on their ability to handle up to four sensors, real time image fusion, open architecture and a relatively small form factor

The report provides an in-depth introduction into image fusion approaches. A list of potential fusion algorithms were identified based upon on the number of times cited, availability of information, and the applicability to night vision image fusion test bed. Algorithms reviewed include the following:

- Pixel Level Image Fusion
    - Simple Averaging Technique
    - Principal Components Analysis (PCA)
- Pyramid Based Fusion Schemes
    - Laplacian Pyramid Algorithm (LAP)
    - Morphological Pyramid Algorithm (MORPH)
    - Gradient Pyramid Algorithm (GRAD)
    - Ratio of Low-Pass Pyramid Algorithm (RoLP)
- Wavelet Transforms (WT)
    - Discrete Wavelet Transform (DWT)
    - Shift-Invariant Discrete Wavelet Transform (SiDWT)
- Feature Level Image Fusion
    - Edge Detection Method
- Decision Level Image Fusion

Recommendations on what fusion algorithms should be examined in the fusion test bed are provided.

The ultimate aim of image fusion is to create a faithful and composite image that retains the important information from the source images while minimizing the noise caused by fusing the images. For the SIHS application, these images will be typically viewed and interpreted (perceived) by an operator. A number of subjective and objective evaluation approaches and metrics have been proposed in the literature to quantify and qualify image fusion performance. While subjective evaluation approaches generally follow a signal detection paradigm, objective approaches differ considerable. Four general approaches to objective evaluation were identified: methods based on statistical characteristics, methods based on definition, methods based on information theory; and methods based on important features. COTS fusion evaluation modules available for use by the Vision SST are provided.

Recommendations on what valid fusion metrics should be utilized in the fusion test bed are provided. Improvements to fusion subjective evaluation approaches are also provided.

Finally, summary suggestions for the Vision SST fusion test bed are provided.

Sommaire

Le rapport a principalement pour objectifs de déterminer et d'examiner le domaine de la fusion d'images et des technologies d'appui, ainsi que de recommander des systèmes, des algorithmes et des mesures pour le banc d'essai de fusion de l'équipe des sous-systèmes de vision, dans le cadre de la démonstration de technologie - casque intégré pour soldat (DT - SIHS). Une recherche de la documentation pertinente a été effectuée dans les bases de données suivantes : PsycInfo, National Technical Information Service (NTIS), SPIE, IEEE, Génie optique, GlobalSpec, Rapports de recherche de la Défense et World Wide Web (www). Les combinaisons « Image Fusion » (fusion d'images) et « Sensor » (capteur), ainsi que « Hardware » (matériel) et « Multi-sensor » (multi-capteurs), ont été utilisées comme mots-clés. Lorsqu'un mot-clé donnait des références impossibles à traiter (en trop grand nombre), on ajoutait systématiquement des mots-clés supplémentaires pour raffiner la recherche. En général, cette façon de procéder a donné de multiples références non pertinentes. Des résultats plus fructueux ont été obtenus des techniques « boule de neige » consistant à débuter par des auteurs et des documents connus, puis à suivre les références qu'ils fournissaient à d'autres ouvrages. À la fin de la recherche, environ 150 documents d'utilité immédiate avaient été trouvés pour l'examen.

Le rapport présente en détail les technologies et les mesures d'évaluation du matériel et du logiciel de fusion. Les facteurs influant sur le rendement sont exposés. L'examen fait également ressortir les tendances de développement applicables à diverses technologies de capteurs, méthodes de fusion et mesures d'évaluation existantes et émergentes. Les travaux visent essentiellement à déterminer les technologies prometteuses de fusion et détection, qui pourraient être utilisées dans le cadre de la DT - SIHS.

L'équipe des sous-systèmes de vision de la DT - SIHS planifie le développement à court terme d'un banc d'essai de fusion permettant de quantifier le rendement des soldats débarqués. Les systèmes examinés dans le cadre de ce projet devraient être au point et compatibles avec les applications portatives d'ici 2007. Plus de 200 capteurs d'imagerie possibles pour la DT - SIHS sont indiqués dans le rapport. Il s'agit notamment des capteurs suivants :

- Caméras de nuit
    - o LLLTV
    - o ICCD
    - o ICMOS
    - o EMCCD
    - o EBCMOS
    - o Hybride CCD/CMOS
    - o CMOS couleur

• Capteurs thermiques
    - o Caméra CMOS à modulateur de lumière thermique (TLV)
    - o SWIR
    - o MWIR/LWIR
    - o SWIR et LWIR fusionnés

L'examen de la documentation a fait ressortir des progrès technologiques considérables en matière de réduction de la taille des capteurs, de réduction de la puissance consommée et d'augmentation de la résolution. Un nouveau système d'imagerie thermique basé sur un filtre optique passif appelé modulateur de lumière thermique pourrait procurer des avantages appréciables dans le cadre des futurs programmes de modernisation du soldat. Les progrès en matière de résolution des caméras à bas niveau de lumière ICMOS et EBCMOS peuvent éliminer la nécessité d'incorporer des LVN à renforcement d'image aux futurs casques. Le rapport analyse des systèmes de capteurs sélectionnés pour établir leur adaptabilité au banc d'essai de fusion en fonction des facteurs de forme des capteurs, de la résolution des détecteurs et du rendement en temps réel. Des recommandations sont incluses quant aux capteurs à intégrer au banc d'essai de fusion.

L'examen de la documentation a également permis de déterminer des cartes de fusion commerciales courantes qui pourraient accélérer le développement du banc d'essai de fusion de l'équipe des sous-systèmes de vision, dans le cadre de la DT - SIHS. Des architectures avancées de système de traitement de fusion sont décrites. Le rapport analyse des systèmes de fusion sélectionnés en fonction de leur aptitude à traiter jusqu'à quatre capteurs, la fusion des images en temps réel, une architecture ouverte et un facteur de forme relativement bas. Le rapport présente en détail des méthodes de fusion d'images. Une liste des algorithmes de fusion possibles est dressée, selon le nombre des citations, la disponibilité de l'information et l'application au banc d'essai de fusion des images de vision nocturne. Les algorithmes suivants sont examinés :

• Fusion d'images au niveau des pixels
    - o Technique d'établissement de moyenne simple
    - o Analyse des composantes principales (PCA)

• Pyramid Based Fusion Schemes
    - o Algorithme pyramidal de Laplace (LAP)
    - o Algorithme pyramidal morphologique (MORPH)
    - o Algorithme pyramidal en gradient (GRAD)
    - o Rapport d'algorithme pyramidal passe-bas (RoLP)

• Transformées d'ondelettes (WT)
    - o Transformée d'ondelettes discrètes (DWT)
    - o Transformée d'ondelettes discrètes invariante par décalage (SiDWT)

• Fusion d’images au niveau des éléments

  o Méthode de détection des bords

• Fusion d’images au niveau des décisions

Des recommandations portent sur les algorithmes de fusion qu’il y a lieu d’examiner pour le banc d’essai de fusion. Le but ultime de la fusion d’images consiste à créer une image fidèle et composite qui conserve l’information importante des images de la source tout en réduisant le bruit causé par la fusion des images. Pour l’application SIHS, ces images seront typiquement visualisées et interprétées (perçues) par un opérateur. Un certain nombre de méthodes et de mesures d’évaluation subjective et objective sont proposées dans la documentation en vue de la quantification et de la qualification du rendement de fusion d’images. Bien que les méthodes d’évaluation subjective soient généralement conformes à un paradigme de détection des signaux, les méthodes objectives diffèrent considérablement. Quatre méthodes générales d’évaluation objective sont déterminées : méthodes fondées sur des caractéristiques statistiques, méthodes fondées sur des définitions, méthodes fondées sur la théorie de l’information et méthodes fondées sur des éléments importants. Des modules commerciaux courants d’évaluation de la fusion sont mis à la disposition de l’équipe des sous-systèmes de vision. Des mesures de fusion valides sont recommandées pour le banc d’essai de fusion. Des détails sont également fournis sur les améliorations qu’il y a lieu d’apporter aux méthodes d’évaluation subjective de la fusion. Enfin, des suggestions sommaires sont présentées pour le banc d’essai de fusion de l’équipe des sous-systèmes de vision.

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1 Introduction

Effective system integration, especially with regard to head-borne systems, remains one of the biggest challenges in soldier modernization R&D. While several allied Soldier Modernization Programs (SMPs) are developing prototype future headwear systems by adding sensing, information display, and communications technologies to existing helmets, little or no progress has been made in integrating enhanced ballistic, Chemical Biological (CB), blast or thermal protection into the system. In fact, in many cases, trade-offs with protection have been made in order to accommodate the specific technologies. Thus, a fully integrated head system design that properly addresses future operational technology requirements, personnel protection, and human factors and performance issues is not the focus of current SMPs. This work is critical to success of the Canadian Land Staff (CLS) Capital Acquisition Program called Integrated Soldier System Platform (ISSP).

The Soldier's Integrated Helmet System Technology Demonstrator (SIHS TD) project will develop and demonstrate *three unique technology concepts* that represent different levels of integration. The concepts will range from a *combined add-on* system where components are added piecemeal to existing headwear systems, through a bottom-up-designed *modular/compatible* approach where subsystem functionality can be added or removed as and when needed, to a *fully and permanently encapsulated* design where weight, space, protection and functionality are optimized maximally.

The SIHS programme will empirically determine the most promising headwear integration concept that significantly enhances the survivability and effectiveness of the future Canadian soldier/warfighter by developing, evaluating, and demonstrating novel concepts for integrating enhanced protection, sensing, information display, and communications technologies into a headwear system (Tack, 2007). To this end SIHS has developed a number of helmet concepts that include novel sensors - see Figure 1.

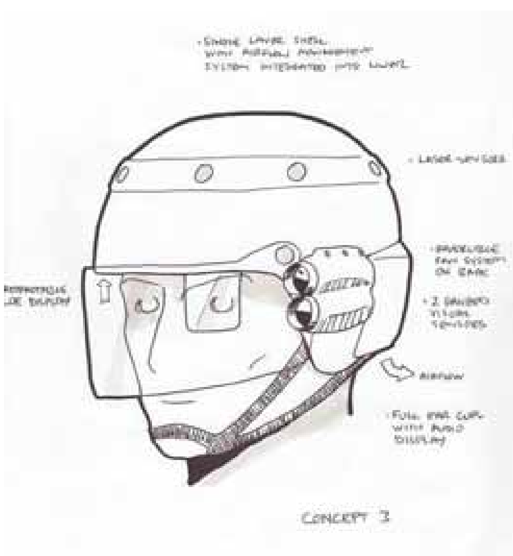

Figure 1: SIHS Concept 3 - C4I/Survivability

A variety of imaging sensors are available for inclusion in the SIHS TD and each sensor has particular strengths and weakness. One proposed approach is to utilize fused sensors (Angel, Vilhena and Morton, 2006a). Multi-sensor image fusion has become a valuable reality in defence applications. The benefits of image fusion have also been demonstrated in a large number of studies (Toet and Ijspeert, 1997; Dixon, Canga, Noyes, Troscianko, Nikolov, Bull and Canagarajah, 2006; Angel and Vilhena, 2005, etc.) The results suggest that the SIHS TD should investigate the impact of fusion on dismounted soldier activities.

In association with Defence Research and Development Canada (DRDC) Valcartier, and the Electro-Optic Test Facility (EOTF) of the United States Marine Corps (USMC), the SIHS TD Vision Sub-System Team (SST) is exploring sensor imagery fusion as part of the SIHS TD. Previously, DRDC Valcartier investigated fusion algorithms and man-portable fusion systems in the past, but this work is now almost five years out of date. The Vision SST and EOTF have developed an initial research proposal to investigate fusion for the SIHS TD. An outline of the proposed work is as follows:

1. Conduct a literature review to identify current fusion capabilities, current hardware, current software algorithms, and any promising technologies for the future.
2. Evaluate algorithm options to more clearly define and understand the various effects and transformations the potential algorithms generate on imagery.
3. Acquire sensors and hardware. In collaboration between DRDC Toronto, DRDC Valcartier and EOTF, sensing devices of interest will be acquired.
4. Identify the required characteristics of raw imagery to be collected for fusion studies. These characteristics should include season, numbers and types of targets (person/vehicle, mobile/stationary or a mixture), and lighting.
5. Collect imagery. EOTF, in collaboration with DRDC Valcartier, will collect the imagery.
6. Conduct psychophysical tests on fusion imagery to quantify operator performance. In collaboration between DRDC Toronto, DRDC Valcartier and EOTF subjective and objective testing will be undertaken.

Given the potential benefits to Canadian and USMC SMPs, support was given to the Vision SST to conduct the state of the art literature review. This report will outline the results of the literature review. The review investigated the latest trends in imaging sensors, fusion hardware, software, and evaluation metrics. Based on the findings of this literature review, a way a head for the Vision SST fusion study will be proposed.

1.1 Electromagnetic Spectrum

A basic knowledge of the electromagnetic spectrum is helpful to understand the current and emerging night vision and vision enhancement technologies. The electromagnetic spectrum is a term to describe the range of energy wavelengths emitted by any object or living creature. All objects emit infrared energy and this amount is proportional to the temperature of the object. Warner objects emit more energy. Figure 2 shows the spectrum. Except for the visible, all spectrums cannot be seen by the human eye. In order to make the non-visible spectrum visible to the human eye, technologies have been developed that convert or amplify energies to the visible spectrum.

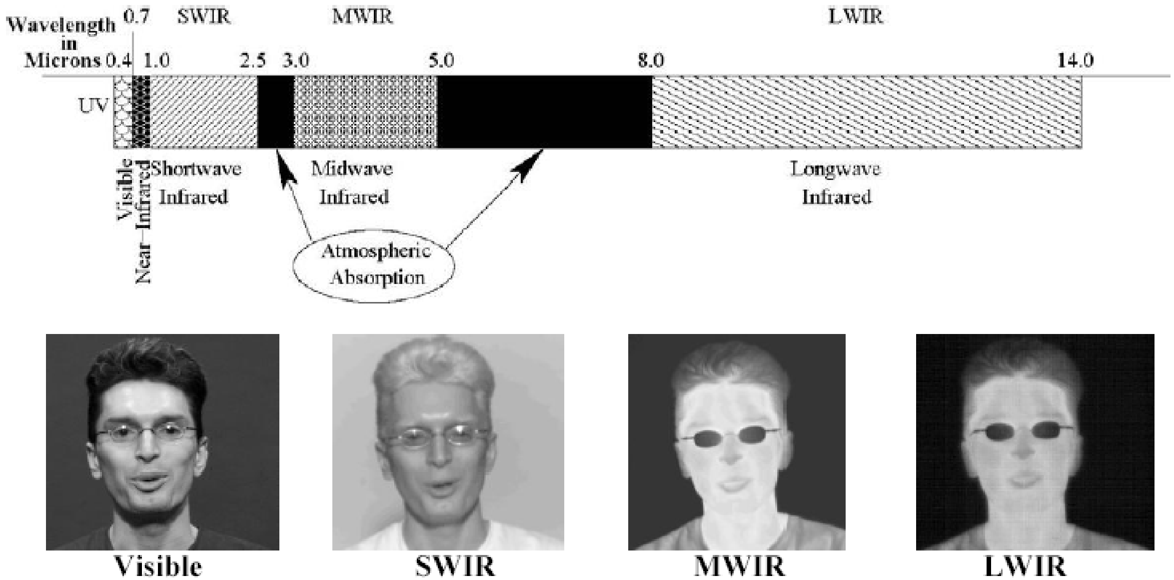

Figure 2: (Top) Nomenclature for various parts of the electromagnetic spectrum (Bottom). A picture simultaneously imaged in various parts of spectrum (Wolff, Socolinsky, Eveland, 2006)

1.2 Applications of Image Fusion

Image fusion of multispectral images has been increasingly studied to enhance performance in military applications. With the growing availability of Commercial-off-the-Shelf (COTS) sensors/cameras, that image in VIS-NIR, SWIR, MWIR, and LWIR, there is a corresponding increase in the practical exploitation of different fusion combinations between any of these respective spectrums (Wolff et al, 2006).

There are numerous applications of image fusion in the military domain. Applications of image fusion for defence applications include automatic target recognition (ATR), identification-friend-foe-neutral (IFFN), and battlefield surveillance and situation assessment. In some applications the degree of fusion may be set by the user to select between sensor fusion outputs. For example, the degree of infrared and thermal may be adjusted and this will vary the hue of the image.

The benefits of multi-sensor image fusion include (Angel, Vilhena, and Morton, 2007):

- Extended range of operation;
- Extended spatial and temporal coverage;
- Reduced uncertainty;
- Increased reliability;
- Robust system performance; and
- Compact representation of information.

The US Defense Advanced Research Projects Agency (DARPA) is currently exploring fusion in its Multispectral Adaptive Networked Tactical Imaging System (MANTIS). The goal of the MANTIS program is to demonstrate a visualization system to regain the night-time advantage for the individual soldier and provide unprecedented situational awareness. MANTIS consists of:

- A head-mounted, multispectral sensor suite (Vis/ NIR/SWIR/LWIR), digital display and an inertial navigation system; and
- A body-worn processor and power supply, to digitize, process, and display fused imagery, augmented reality and battlefield information in real time. MANTIS will provide small units with network-enabled, collaborative visualization for soldier-to-soldier image sharing, access to remote sensors and targeting handoff to off-board weapons, allowing the soldier to point, click and kill.

2 Aim

The purpose of this project was to identify and review the field of image fusion and contributing technologies and to recommend systems, algorithms and metrics for the proposed SIHS TD Vision SST fusion test bed.

2.1 Abbreviations

AGC	Automatic Gain Control
ATR	Automatic Target Recognition
AUG	Airborne Underwater Geophysical
CB	Chemical Biological
CCD	Charge Coupled Device
CISTI	Canada Institute for Scientific and Technical Information
CLS	Canadian Land Staff
CMOS	Complementary Metal-Oxide-Semiconductor
COTS	Commercial-Off-the-Shelf
DARPA	Defence Advanced Research Projects Agency
DRDC	Defence Research and Development
DSCQE	Double Stimulus Continuous Quality Evaluation
DWT	Discrete Wavelet Transform
EBAPS	Electron Bombarded Active Pixel Sensor
EBCMOS	Electron Bombarded CMOS
EMCCD	Electron Multiplying CCD Charge Coupled Device
ENVG	Enhanced Night Vision Goggle
EOTF	Electro-Optic Test Facility
FLIR	Forward-Looking Infra-red
FOV	Field Of View
FPA	Focal Plane Array
FSD	Filter Subtract Decimate

GaAs	Gallium Arsenide
GIFT	Generalised Image Fusion Toolkit
GRAD	Gradient Pyramid Algorithm
HMD	Helmet Mounted Display
HSI	Humansystems Inc.
I^2 or II	Image Intensified
ICCD	Intensified CCD
ICMOS	Intensified Complementary Metal-Oxide-Semiconductor
IEEE	Institute of Electrical and Electronics Engineers
IFFN	Identification-Friend-Foe-Neutral
IFPM	Image Fusion Performance Measure
InGaAs	Indium Gallium Arsenide
IQI	Image Quality Index
IR	Infrared
ISSP	Integrated Soldier System Platform
ITK	Insight Toolkit
LADAR	Laser Detection And Ranging
LAP	Laplacian Pyramid Algorithm
LLL	Low Level Light
LLLTV	Low Level Light Television
LWIR	Long Wave Infrared
MANTIS	Multi-Spectral, Adaptive, Networked Tactical Imaging System
MBTI	Myers-Briggs Type Indicator
MI	Mutual Information
MORPH	Morphological Pyramid Algorithm
MOS	Mean Opinion Score
MR	Multi-Resolution
MSD	Multiscale-Decomposition
MWIR	Medium Wave Infrared
NATO	North Atlantic Treaty Organisation
NGEOS	Northrop Grumman Electro-Optical Systems
NIR	Near Infrared
NMSD	Non-Multiscale-Decomposition
NTIS	National Technical Information Service
NVD	Night Vision Device
NVESD	Night Vision and Electronic Sensors Director/Directorate (US Army)
NVG	Night Vision Goggle
PCA	Principal Component Analysis
PSNR	Peak Signal to Noise ratio
Q	Fusion Quality Measure/Index

QE	Edge Dependent Fusion Quality Index
QMF DWT	Quadrature Mirror Filter Discrete Wavelet Transform
QW	Weighted Fusion Quality Index
QWIP	Quantum Well Infrared Photo Detector
R&D	Research and Development
RMSE	Root Mean Square Error
ROC	Receiver Operating Characteristic
ROIC	Read Out Integrated Circuit
RoLP	Ratio of Low Pass Pyramid Algorithm
SA	Situational Awareness
SF	Spatial Frequency
SiDWT	Shift-invariant Discrete Wavelet Transform
SIHS TDP	The Soldier Integrated Headwear System Technology Demonstrator
SIT	Silicon Intensified Target
SMaRTS	Soldier Mobility and Rifle Targeting System
SMPs	Soldier Modernization Programs
SNR	Signal Noise Ratio
SPIE	The International Society for Optical Engineering
SSCQE	Single Stimulus Continuous Quality Evaluation
SST	Sub-System Team
STINET	Scientific and Technical Information Network
SWIR	Short Wave Infrared
TBIR	Target-Background Interference Ratio
TI	Thermal Imaging
TIR	Target Interference Ratio
TNO	Netherlands Organisation for Applied Scientific Research
UIQI	Universal Image Quality Index
USMC	United States Marine Corps
VDA	Visual Difference
VIS	Visible
VOx	Vanadium Oxide
WT	Wavelet Transforms
WWW	World Wide Web

3 Method

This section outlines the methodology used in this scientific/academic search. Given the broad areas to investigate, a three member team approach was utilized. Each member of the team was primarily responsible for one area of the research:

- Hardware – sensors, fusion boards;
- Software – fusion algorithms; and
- Factors – evaluation metrics.

3.1 Keywords

A set of keywords were developed by the project team for the literature search based on our experience with the pertinent technological, scientific, and military domains. These keywords were chosen because they focused the search on topics directly related to sensor fusion, sensor hardware, software, and evaluation metrics. The following keywords (Table 1) were used in combination to search easily accessible databases. The words were used in combination (one word from primary, then one word from secondary would be added, then one word from tertiary would be added until all combinations of primary with secondary with tertiary words are searched). If an unmanageable number of hits results from a search with three words, additional modifiers (from the keyword list) were used to focus the results.

Table 1: Primary, secondary and tertiary keywords for sensor fusion, hardware, software, and metrics

Core Concept	Primary Keywords	Related Keywords
Image Fusion	Systems	Indirect view, direct view, emerging, enhanced, low light, optical, digital, biologically-inspired, range-gated Multi-sensor fusion
Application Area	**Primary Keywords**	**Related Keywords**
Sensor	LLLTV CCD I^2 NIR CMOS EBAPS TI SWIR MWIR LWIR DAY Visible FLIR IR	Night vision goggles, weapon sights, hand-held systems, tripod mounted systems, thermal sights, UAV Vendors: DRS Technologies, Woodburn, Northrop Grumman, Sensors Unlimited, Nivisys, Insight technology, Elcan, FLIR Systems, Stanford photonics
Hardware	Sensor fusion processors Video processing boards	Image, video capture cards Vendors: Octec, Equinox, Sarnoff, TNO, NVESD

Core Concept	Primary Keywords	Related Keywords
Software	Algorithms, image fusion, pixel level, feature level, decision level	Techniques, analysis, methods, shift invariant discrete wavelet transform, Laplacian pyramid, principle component, filter-subtract-decimate (FSD), gradient, Gaussian pyramid, morphological, contrast pyramid, ratio of low pass pyramid, contrast
Metrics	Evaluation, analysis, measure Performance Objective Subjective Quantitative	Total probability density function Comparative, quantifying Image quality index Fusion quality index Quantitative correlation index Mutual information Weighted fusion quality index Edge dependent fusion quality index Spatial detail Spectral information Spatial resolution Signal to noise Distortion Fisher distance Fechner-Weber contrast Target-background interference ratio (TBIR)

The core concept keywords were the most important words used in the search, as they represent the broad concepts to be investigated. As necessary, the primary keywords were used in order to ensure sampling of literature from several different areas within the core concept. For example, when searching with the “sensor” core concept, primary keywords such as “NIR” and “LLLTV” may or may not emerge. The purpose of the primary keywords was to ensure that research related to several different aspects of sensor fusion was explored.

3.2 Databases

The following were primary databases that were the most relevant for searching the scientific/academic literature:

Table 2: Primary Databases for Scientific/Academic Search

Database	Description
SPIE – The International Society for Optical Engineering	The SPIE Digital Library is a resource for optics and photonics information. It contains more than 70,000 full-text papers from SPIE Journals and Proceedings published since 1998. It also includes citations and abstracts for most SPIE papers published since 1993. Approximately 15,000 new papers will be added each year. (SPIE, 2007)
IEEE – Institute of Electrical and Electronics Engineers, Inc	The IEEE, a non-profit organization, is the world's leading professional association for the advancement of technology. The IEEE publishes nearly a third of the world’s technical literature in electrical engineering, computer science and electronics. This includes about 130 journals, transactions and magazines and over 400 conference proceedings published annually. IEEE journals are consistently among the most highly cited in electrical and electronics engineering, telecommunications and other technical fields. (IEEE, 2007)
NTIS – National Technical Information Service	NTIS is an agency of the U.S. Department of Commerce’s Technology Administration. It is the official source for government sponsored U.S. and worldwide scientific, technical, engineering, and business related information. The database contains almost three million titles, including 370,000 technical reports from U.S. government research. The information in the database is gathered from U.S. government agencies and government agencies of countries around the world. (NTIS, 2007)
CISTI – Canada Institute for Scientific and Technical Information (CISTI)	CISTI houses a comprehensive collection of publications in science, technology, and medicine. It contains over 50,000 serial titles and 600,000 books, reports, and conference proceedings from around the world. (CISTI, 2007)

The following were secondary databases for searching the scientific/academic literature:

Table 3: Primary Databases for Scientific/Academic Search

Database	Description
STINET – Scientific and Technical Information Network	STINET provides access to citations of unclassified unlimited documents that have been entered into DTIC's Technical Reports Collection, as well as the electronic full-text of many of these documents. Public STINET also provides access to the Air University Library Index to Military Periodicals, Staff College Automated Military Periodical Index, DoD Index to Specifications and Standards, and Research and Development Descriptive Summaries. (STINET, 2007)
GlobalSpec	GlobalSpec is the leading specialized vertical search, information services and e-publishing company serving the engineering, manufacturing and related scientific and technical market segments. GlobalSpec has I/PRO audited Web site traffic, and a global user base of more than 3,400,000 registered users; a user community that continues to grow by more than 80,000 new registrants each month. In addition, the company has acquired 3,500,000 opt-in, online readers of its suite of product-specific e-newsletters that cover the electrical and mechanical engineering products markets, as well as other segments of the electronics, scientific and manufacturing industries. GlobalSpec is increasingly becoming "the place" where the engineering community gathers and conducts business. (GlobalSpec, 2007)

In addition, the World Wide Web (www) was searched with all the keywords.

3.3 Search Strategy

The project team systematically searched the databases using the keywords specified. For example, the first keyword search series consisted of the core concepts listed in Table 1: "Image Fusion" and "Sensor", "Hardware" and "Multi-sensor". Other searches at this level used primary keyword variations, for example, "Indirect view" and "multi-sensor". When a keyword yielded an unmanageable (too many) number of references, the researcher systematically added additional primary keywords to refine the search. When a keyword yielded too few searches, less narrow concepts were used until the precise level of analyses has been reached.

Once core concept and primary keyword searches were conducted within the primary databases, all abstracts were reviewed. In the case of the GlobalSpec database, all product information sheets were reviewed.

Secondary databases were explored in order to ensure that sensor fusion products (hardware and software) were accessed. The research team reviewed abstracts or technical data sheets for adequacy of relevance, quantity, and quality. If necessary, searches were refined and/or revised and continued using secondary level keywords. The project manager benchmarked the "hits" found during the search with and they are reported in the Results section.

3.4 Analysis of Literature

Given the research area there were multiple foci in the review of articles: first, to identify specific sensor and hardware technologies available, second, to identify the most promising fusion approaches available, and third, robust metrics to evaluate fusion performance. Once identified, the critical characteristics of each focus area were compiled, i.e. for sensors critical characteristics included size, resolution, frame rate etc. The articles/approaches reviewed in the literature search were then assessed using the relevant criteria.

4 Results

The results from the literature search are organized as follows:

- Hardware – sensors, fusion boards;
- Software – fusion algorithms; and
- Factors – evaluation metrics.

4.1 Hardware

Both sensors and fusion boards were reviewed. Although over 200 sensors were identified in this review, only those that were judged suitable for the SIHS TD application are presented. A summary of the sensor specifications, organized by type, is provided in Annex A.

Seven fusion boards were also identified during this review. A summary of the board specifications is provided in Annex B.

4.1.1 Sensors

The results below present information on several different sensor types: Day-night cameras, LLLTV, ICMOS, EMCCD, EBCMOS, Colour CMOS, SWIR, MWIR and LWIR. A comparative analysis of potential sensors is organized by type in the Discussion Section (Section 5).

4.1.1.1 Day-Night Cameras

Unlike many security cameras which require high intensity Light Emitting Diodes (LEDs) to illuminate their targets, a number of high performance cameras are available for use in low light and full sun conditions. Typically these full range cameras include signal enhancements in low light. The DVS24-1000 from Defence Vision Systems camera – see Figure 3, provides a high resolution image across a wide dynamic range.

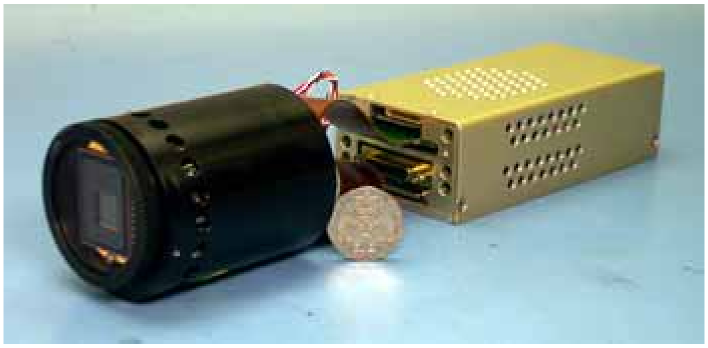

Figure 3: Defence Vision Systems day-night camera DVS24-1000 from http://213.210.6.54/dvsmil

Day-night cameras typically monitor scene illumination (auto gain) and can control an auto iris for use with custom lenses. The performance of day night cameras at night does compare to the performance of dedicated night cameras.

4.1.1.2 Low Level Light Television (LLLTV)

LLLTV cameras are used in low light level conditions. There are a few distinct groups of LLLTV cameras: Silicon Intensified Target (SIT) tube cameras, Intensified Silicon Intensified Target (ISIT) tube cameras, Intensified Charge Couple Device (ICCD) cameras, and cooled CCD cameras. The LLLTV sensor typically couples an Image Intensifier (I^2) tube with a Charged Couple Device (CCD). Images produced from the intensifier tube are displayed on the intensifiers phosphor screen. These images are relayed to a CCD camera by a fibre optic coupler or a simple relay optic. with a frequency detection range extending above the normal visible (0.4 to 0.7 µm) wavelengths, and into the short-wave Infrared that is usually to about 1.0 to 1.1 µm. The coupling of an image intensifier tube to a CCD range allows the human eye to see objects in extremely low light levels. The LLLTV sensor technology reduces the images into a series of lines.

It is possible to improve the performance of a non-intensified CCD detector by cooling the detector and using long integration times to reduce noise. While cooled CCD cameras can reach the performance of ICCD cameras, the camera requires long integration times for detection, i.e. not suitable for real time applications.

Figure 4: Micro ICCD camera system from Defence Vision Systems (from http://213.210.6.54/dvsmil/PDF)

ICCD based sensors use a special manufacturing process that creates the ability to transport charge across the chip without distortion, whereas the Complementary Metal Oxide Semiconductor (CMOS) sensor uses a traditional manufacturing process as most microprocessors. CCD based sensors create high-quality, low-noise images, whereas CMOS sensors are more susceptible to noise. Furthermore, the CCDs have been in mass production for a long period of time, therefore they are more mature and tend to have higher quality images compared to CMOS.

LLLTV cameras can be used in many applications. The findings of our literature review showed that many of the applications are primarily for scientific and industrial applications. For example, LLLTV sensors are used in near-IR cellular, dermal, machine vision, high-content screening, and manufacturing inspection. In terms of military applications, they are used in surveillance imaging applications.

Annex A contains a list of fifteen LLLTV cameras/sensors that would be suitable for the SIHS application. From these products identified, there were four different manufacturers: DVC, Intevac, NAC Image Technology, and PCO Imaging.

4.1.1.3 Intensified Complementary Metal Oxide Semiconductor (ICMOS) Sensor

CCD cameras have been replaced in many commercial applications by Complementary Metal-Oxide-Semiconductor (CMOS), or camera-on-a-chip, systems. CMOS image sensors operate at lower voltages than CCD, resulting in less power consumption for dynamic applications, such as a helmet mounted system. CMOS cameras also have simpler design and may be integrated more easily than a CCD. As with CCD cameras, CMOS cameras can be coupled with intensifier tubes creating ICMOS sensors – see Figure 5. There are two categories of ICMOS image sensors: analog and digital. Analog and digital processing functions can be integrated readily onto a CMOS chip. This reduces system package size and overall costs.

Figure 5: I^2 bonded CMOS image sensor

CMOS chips can be manufactured on any standard silicon production line, thereby making them less expensive than a CCD sensor. Other advantages of CMOS sensors include (Beyondlogic, 2005):

- No blooming;
- Low power consumption. Ideal for battery operated devices;
- Direct digital output;
- Small size and little support circuitry Often just a crystal and some decoupling; and
- Simple to design with.

Annex A contains a list of seven ICMOS cameras/sensors that would be suitable for the SIHS application. From these products identified, there were five different manufacturers: Intevac, Irvine Sensors Corp., PCO Imaging, Prosilica Inc, and Vision Research Inc.

4.1.1.4 Electron Multiplying Charge Coupled Devices (EMCCD)

While an ICCD camera utilizes an image intensifier is placed in front of the CCD chip to enhance its light detection an Electron Multiplying CCD (EMCCD) camera uses an alternative approach to a standard image intensifier. EMCCD cameras are currently being developed for special scientific applications (microscopy, spectroscopy, etc.)- see Figure 6.

Figure 6: CoolView EM/1000 EMCCD camera (from http://www.photonic-science.co.uk/zz_CoolView_EM.html)

EMCCD cameras utilize a “gain register” electron multiplying structure. The gain register performs the same function of the intensifier microchannel plate but creates new electrons. EMCCD cameras need to be cooled to reduce readout noise (for the Coolview EM/100 this is in the order of –50°C).

Evaluations of EMCCD by Dussault and Hoess (2004) did not demonstrate advantages of using uncooled EMCCD cameras over ICCD systems – see Figure 7. While EMCCD cameras may be a credible alternative to ICCDs for some applications, they are not believed to be adequate for SIHS TD applications.

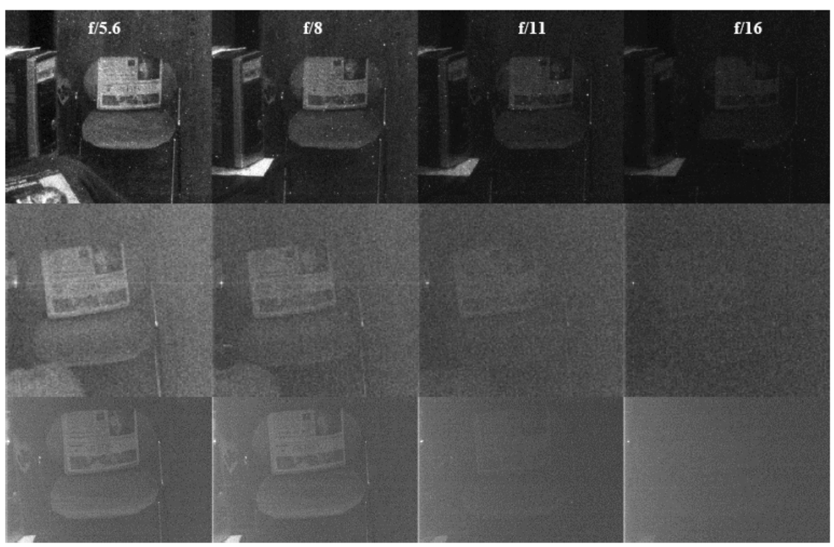

Figure 7: EMCCD and ICCD Camera comparison in low ambient light conditions

Top row: Stanford Photonics XR-Mega-10 Extreme 1400 x 1024 pixels ICCD detector, 33 msec exposure, no binning. Middle row: Andor EEV iXon EMCCD camera (512 x 512 pixels), 33 msec exposure, no binning. Bottom row: Roper Cool Snap 1400 x 1024 CCD, 33 msec exposure, binned 2x2. (from Dussault and Hoess (2004)

4.1.1.5 Electron Bombarded CMOS (EBCMOS) Sensor

The Electron Bombarded CMOS (EBCMOS) sensor is a relatively new type of sensor. Intevac has patented the first EBCMOS technology called the Electron Bombarded Active Pixel Sensor (EBPAS). EPABS is based on the use of GaAs (Gallium Arsenide) photocathode with a high resolution, backside thinned, CMOS Active Pixel Sensor (APS) imager anode. The photocathode emits electrons directly to the CMOS APS anode in an electron bombarded mode. A low noise gain is achieved in the CMOS anode due to the Electron Bombarded semi-conductor gain process. The noise generated in the EBAPS is significantly lower than the noise output in the Generation-III I² module. This low noise gain advantage is combined with modern semi-conductor packaging and manufacturing approaches to enable a small EBAPS module that can be mass produced at a low cost. (from http://www.intevac.com/imaging/technology)

The use of CMOS imagers enables the EBAPS sensor to address some of the key deficiencies found in previous Low Light Level Cameras such as, size, and increased power consumption. The ultimate performance of the EBAPS depends on the architecture and design of the CMOS imager and the ability to produce an area with a 100% fill factor (no dead area). The EBAPS also achieves high performance through the use of the high efficiency GaAs Photocathode which is sensitive in the Near-IR region of the electromagnetic spectrum.

The EBAPS based camera has significant performance differences relative to a standard I² camera. Since the EBAPS does not utilize a microchannel plate it can be operated in a day only mode with no high voltage applied to the sensor. This mode of operation enables high performance near-IR imagery to be obtained in the day without any impact on the sensors operational life.

The new EBAPS ISIE10 camera developed by Intevac surpasses all previous EBAPS models due to its reduction in noise from the CMOS imager and the increase in sensor size by enlarging the pixel size to 10.9 µm. The development of CMOS imagers directly affects the performance of EBAPS sensors. With new generation CMOS imagers the resolution of the EBAPS substantially increases, as well as, increases in the performance of target recognition measures.

The EBAPS camera offers substantially smaller size and weight than present Low Light Level cameras. The EBAPS also has a low sensor profile of approximately 3 cm compared to standard I² goggles. This reduces the likelihood of entanglement in an operational environment, as well as, places the centre of gravity in a more favourable position with respect to the neck. The performance of the EBAPS ISIE10 is thought to rival the Gen-III NVG goggle but in a much more favourable package.

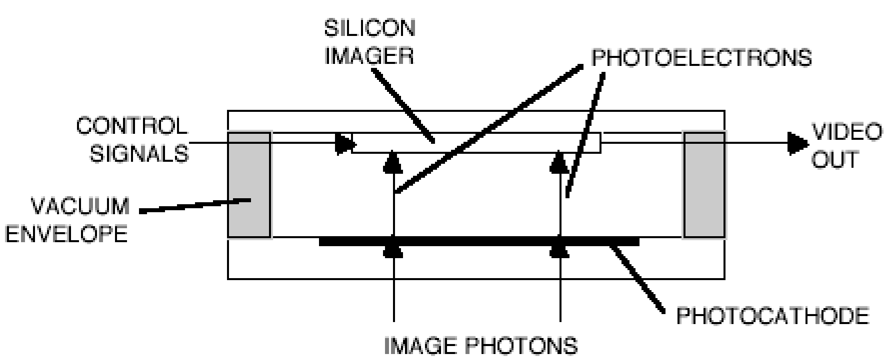

Figure 8: EBAPS design (Aebi et al, 2005)

Annex A contains a list of three EBAPS cameras/sensors that would be suitable for the SIHS application. From these products identified, there was only one manufacturer, Intevac. A report presented by Aebi et al. (2005) to the OPTRO 2005 International Symposium describes the advantages of the EBAPS system over current systems. That information provides the basis for the summary presented here.

4.1.1.6 CCD/CMOS Hybrid

Fairchild Imaging has created a CCD/CMOS hybrid Focal Plane Array (FPA) for low light level imaging applications. This approach combines the best of CCD imaging characteristics: high quantum efficiency, low dark current, excellent uniformity, and low pixel cross talk, with the high speed, low power and ultra-low read noise of CMOS readout technology (Liu, Fowler, Onishi, Vu, Wen, Do, and Horn, 2005). The FPA has two components: two CMOS readout integrated circuits (ROIC) and a CCD imaging substrate (see Figure 9). This has been used in a LLL camera.

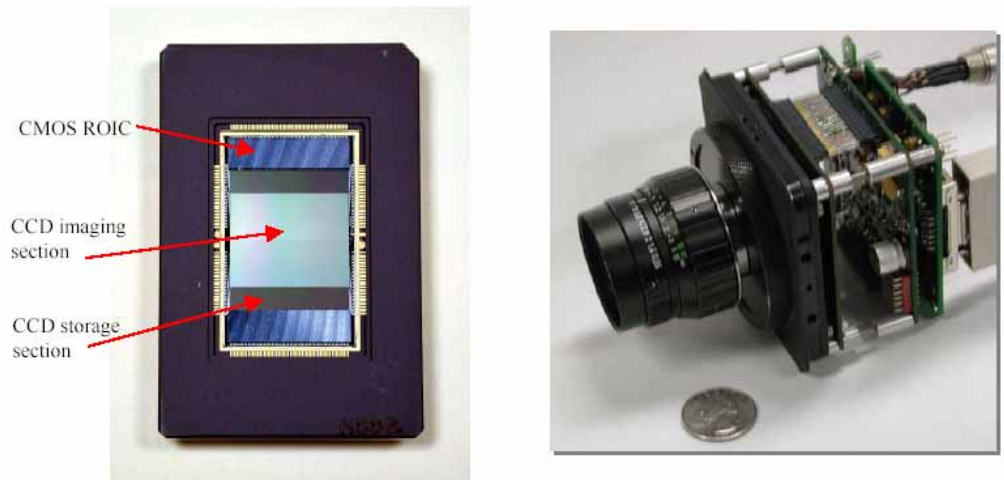

Figure 9: Prototype CCD/CMOS hybrid FPA and low level light camera (Liu et al, 2005)

The above architecture eliminates the slow speed, high noise, and high power limitations of a conventional CCD which would result in a compact, low power, ultra-sensitive solid-state FPA that can be used in low light level applications. Some applications identified by Fairchild Imaging include: live-cell microscopy and security cameras at room temperature operation. The prototype FPA has a 1280 x 1024 format with 12-µm square pixels.

4.1.1.7 Colour CMOS Cameras

The loss of situational awareness with monochrome night vision cameras and sensors, has led to the development of colour night vision systems - . These systems are sensitive to the visible to near-infrared (VNIR) portion of the spectrum. The systems display a rendition of the “colours” that would be seen by the observer in daylight conditions – see Figure 10. The literature review identified a number of colour night vision cameras and goggles.

Three different “True-color” night vision approaches to providing colour are available from the OKSI Opto-Knowledge Systems. One approach utilizes a fast-switching liquid crystal filter in front of a custom Gen-III image intensified CMOS camera, while the second is based around an EMCCD sensor with a mosaic filter applied directly to the detector. The third approach utilizes an ICMOS camera with Liquid Crystal Filter – see Figure 11.

Figure 10: Monochrome and color low-light-level imagery (from http://www.techexpo.com/WWW/opto-knowledge)

Figure 11: True-color night vision camera (ICMOS camera with Liquid Crystal Filter) (from http://www.techexpo.com/WWW/opto-knowledge)

The Tenebraex Corporation has another approach to colour night vision. They have two helmet mounted models at the final preproduction stage. The color products are called the ColorPath™ CCNVD (Color Capable Night Vision Device) – see Figure 12. It uses a standard, green image intensifier tube and a mechanical filter. Tenebraex reports that "the CCNVD can generate a color image down to quarter-moon light levels. At lower light levels, with the Model OP, a simple twist of a knob moves the ColorPath technology from the optical path, leaving the user with a standard, monochromatic green night vision device with all the overcast moonless night performance that he had before."

Figure 12: ColorPath CCNVD, Model MC (from http://camouflage.com/colornightvision.php)

The resolving performance of colour night vision goggles and cameras is currently not as good as dedicated monochrome systems. While manufacturers are currently improving their systems, they are not mature or capable enough to consider for SIHS. By the time of ISSP Build #2, the systems may be potential candidates.

4.1.1.8 Thermal Light Valve (TLV) CMOS Cameras

A new development in thermal imaging is the use of a passive optic filter which translates thermal radiation into light which is imaged by a standard CMOS camera. Unlike other thermal technologies which use microbolometers, QUIPs, etc this system uses relatively simple technologies. This technology was first demonstrated in the laboratory by Aegis Semiconductor in 2004, their spin off company RedShift Systems is now beginning to market the technology.

According to Redshift Systems' website (From http://www.redshiftsystems.com /site/ImagingTechnology/ThermalLightValve) the core of their technology is Thermal Light Valve (TLV) – see Figure 13. The "TLV is a tunable filter composed of pixels standing on thermally isolating posts on an optically reflective and thermally conductive substrate. Each pixel acts as a passive wavelength converter. Using standard thermal optics, long-wavelength infrared (LWIR) radiation from the scene is imaged onto and absorbed by the TLV. This heats up select thermal pixels on the array in direct relation to the thermal signature of the scene. The minimum reflective wavelengths of the pixels shift based upon the thermal energy incident on each. A narrow-band near-infrared (NIR) light source is used to "probe" the temperature of the pixels across the TLV. This NIR probe signal is reflected off the TLV in varying amounts, depending on the pixel temperature, onto the CMOS imager. The intensity of the light received by the CMOS imager is therefore "modulated" by the heat signature of the scene. A thermal image is obtained by measuring the pixel-to-pixel variation in transmission of the NIR probe signal using CMOS imagers."

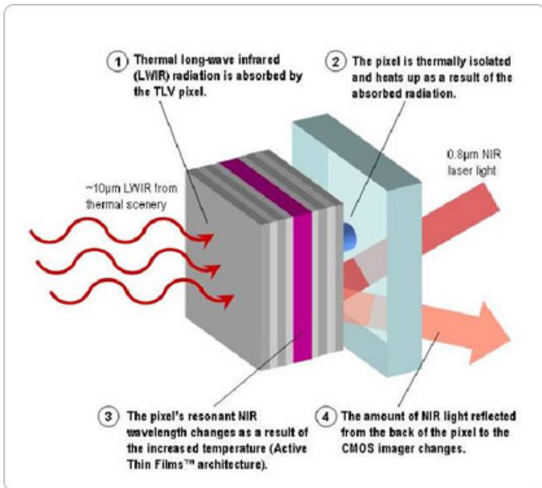

Figure 13: Depiction of the Thermal Light Valve (from http://www.redshiftsystems.com)

While the core of Redshift's technology is the TLV, the system requires a CMOS sensor, a laser diode, lenses and a video processing board. OpTIC is RedShift's brand name for its Optical Thermal Imaging Camera engines – see Figure 14.

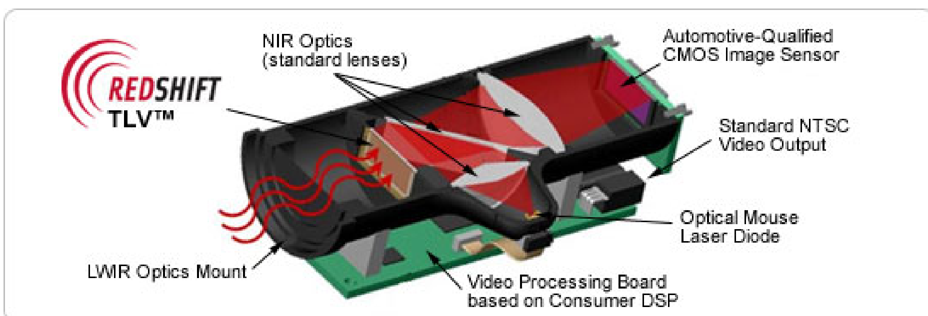

Figure 14:OpTIC camera (from http://www.redshiftsystems.com/site/ImagingTechnology/CameraEngines)

Currently OpTIC engines are limited to 160x120 resolution. While the performance of thermal sensors based upon OpTIC have not been identified in the open literature, the scalability, low cost, low power and potential performance may make this technology suitable for ISSP.

4.1.1.9 Short Wavelength Infrared (SWIR) Sensors

The Short Wave Infrared (SWIR) spectrum covers the 1.1 to 2.5 µm. Typical applications include pharmaceutical, medical diagnostics, food and quality control.

A number of light weight SWIR sensors are currently available as COTS items. Sensors Unlimited has produced several light weight SWIR systems. An example is their SU320KTX (see Figure 15) uses indium gallium arsenide (InGaAs) technology and is being used in the US SMaRTS (Soldier Mobility and Rifle Targeting System) and in the DARPA MANTIS (Multi-Spectral, Adaptive, Networked Tactical Imaging System) project.

Figure 15: SU320KTX SWIR

SWIR detectors are being developed with upper limits extending to 2200 nanometers. These systems are being developed for extended wavelength range hyperspectral imaging for more effective camouflage detection and identification. These 2200 nanometer wavelength devices will also go into long-wave LADAR systems using 1.95 micrometer wavelength lasers (Angel et al, 2007).

Specially processed InGaAs SWIR detectors are being developed to cover the range from 400-1700 nanometers (note the visible spectrum ranges in wavelength from .4 to .7 µm and the NIR section typically spans 0.7 – 1.5 µm.). These shorter-wavelength devices enable the military to see 850 nanometer lasers (AN/PAQ-4C, etc.) as well as the developmental 1.06 and 1.55 µm lasers, along with the visible image (day) of the target being illuminated.

SWIR imagers are being investigated as possible replacements for LLLTV, ICMOS or NVG systems. The image appears as a gray scale picture – see Figure 16.

Figure 16: SWIR camera image

Annex A contains a list of ten SWIR cameras/sensors that would be suitable for the SIHS application. From these products identified, there were four different manufacturers: FLIR, Intevac, Sensors Unlimited Inc., and Lumitron.

4.1.1.10 Mid Wavelength Infrared (MWIR) and Long Wavelength Infrared (LWIR) Sensors

These "thermal" cameras typically cover ranges in the electromagnetic spectrum from 3 to 5 µm (MWIR) and 8 to 12 µm (LWIR). MWIR and LWIR sensors have many industrial as well as military applications. Industrial applications include: wireless communications, spectroscopy, weather forecasting, and astronomy; and military applications include: target acquisition, tracking, and surveillance.

Northrop Grumman Electro-Optical Systems (NGEOS) has focused in recent years on the development of enhanced night vision goggles (ENVG) systems. In 2003, they developed an NVG with the capability of producing real-time image fusion from an I^2 sensor and an uncooled LWIR sensor concentrating on both optical overlay and digital image fusion. This technology allows for optimum imaging in battlefield obscured and laser polluted environment (Estrera, Ostromek, Isbell, and Bacarella, 2003).

In general, MWIR and LWIR cameras are much more expensive than LLLTV cameras. However, MWIR and LWIR cameras generally have better performance/detection.

Annex A contains a list of 25 MWIR and LWIR cameras/sensors that would be suitable for the SIHS application. From these products identified, there were six different manufacturers: DRS NVEC, ELCAN (Raytheon), FLIR, Irvine Sensors, L3 Communications Thermal Eye, and Lumitron.

4.1.2 Commercial Fusion Development Efforts

Along with the continuous development of their own sensors, a number of companies are currently developing fusion systems for commercial and military applications. One of our research team members had the opportunity to attend the USMC Systems Command Infantry Weapons Systems Product Group 13 Optics and Non-Lethal Systems briefing to industry on 24 October 2006. Numerous key industry players were in attendance to present their products and future plans for sensor fusion. Table 4 highlights companies and the sensors they plan to fuse. For example, Northrop Grumman plans to fuse LWIR and I^2CMOS.

Table 4: Future sensor fusion types

	NIR LLLTV	NIR I^2	I^2CMOS	TI	SWIR	LWIR	DAY	Visible	I^2	FLIR	IR
NIR LLLTV											
NIR I^2				Optics1							
I^2CMOS											
TI									Elcan, FLIR		
SWIR		Woodburn				Nivisys, Insight Technology					
LWIR	DRS Techonologies		Northrop Grumman								
DAY						Nivisys					
Visible					Sensors Unlimited						
I^2			Northrop Grumman								Northrop Grumman
FLIR									DRS Techonolo		
IR											

The majority of the current research is on the fusion of just two sensors. There were also presentations regarding fusion of three or more sensors. In particular, Optics1 is planning to fuse thermal with NIR and SWIR. Northrop Grumman plans to eventually fuse sensors using 3 channel fusion for visible/NIR, SWIR, and LWIR.

4.1.3 Fusion Processing System

In addition to sensor cameras, a fusion system requires a number of hardware components, they include frame grabbers or digital input cards; raw image processing cards (warping for registration, noise cleaning, contrast enhancement, and adaptive dynamic range compression, etc.), fusion processing card, data input card, display card, host card etc. The system developed by Fay et al. (2000) for their colour fusion study (2000) utilized a number of electronic cards and boards– see **Error! Reference source not found.**.

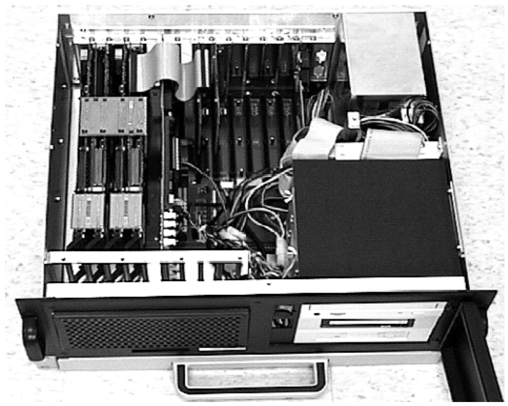

Figure 17: Fusion processing system utilized by Fay et al. (2000)

Fusion processing systems can de developed using readily available PCI-based video processing boards, frame grabbers, backplane mother boards, Video Graphics Array (VGA) adapter boards, etc. Another approach is to develop stand alone Digital Signal Processor (DSP) systems. DSP systems require the need to develop drivers for frames grabber, display, etc. Hines, Rahman, Jobson, and Woodell (2006, June) utilized a single TI DM642 digital signal processor for the fusion system developed for their Enhanced Vision System (EVS).

4.1.3.1 Dedicated Fusion Board

Another approach for the SIHS Vision SST in developing a fusion processing system is to utilize dedicated COTS fusion boards. The following criteria were developed for selecting a stand alone fusion board:

- Able to handle up to four sensors (digital sources TBC);
- Real time fusion;
- Open architecture to implement algorithms of choice; and
- Small form factor.

Many of the boards that were identified in the preliminary search were too large or bulky for the SIHS TD purpose. In addition, many of the fusion boards possessed proprietary or single source fusion algorithms. A total of seven fusion boards were identified as candidates, however only two met the desired characteristics for SIHS TD.

Equinox Corporation has developed a line of image fusion products. The concept is a single unified video image fusion device that can centrally interface with a variety of input cameras and output displays, together with a suite of algorithms that support image fusion across different combinations in the spectrum. These devices are small in size, lightweight and have relatively low power consumption. The key issues for practical field usage are how to effectively visualize two complementary modalities at video rates with sufficiently low power consumption and a small form factor (Wolff, Socolinsky, and Eveland, 2006).

Figure 18 shows Equinox's DVP-4000 hardware for image fusion of two inputs. They have implemented a visually intuitive computational image fusion algorithm with ancillary computational features such as non-linear image modality co-registration and automatic gain control (AGC) onto a compact board.

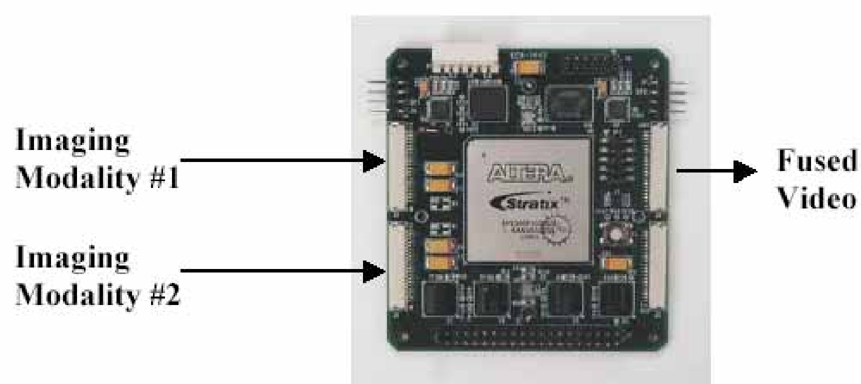

Figure 18: Equinox's DVP-4000 dual video processing board (Wolff et al, 2006)

Similar to Equinox's DVP-4000 is Imagize's FP-3500. It is Imagize's smallest board and has lower power requirements then e Equinox's model. The FP-3500 is able to fuse input images of different sizes and produce a high resolution (1600 x 1200) output image. The Equinox Corporation and Imagize seem to dominate the real-time image fusion processor industry. The Equinox models use an open source for the input of algorithms developed by Waterfall Solutions (Surrey, England). The Imagize model uses a closed system algorithm approach and uses algorithms based on biological vision systems but fail to disclose which algorithms. Octec Image Processing produces a video tracker that is capable of fusing videos and contains multiple analog video and digital video outputs, as well as, multiple analog outputs with the ability of integrating multiple algorithms. For desktop and open source applications the ADEPT60 from Octec appears to be the primary image processor used in literature - See Figure 19 . There are several other companies that develop frame grabbers that are able to select certain frames from the input videos where they are then passed on to the fusion process.

Figure 19: Octec's ADEPT60 automatic video tracker/ image processor

4.1.3.2 Purpose-Built Fusion System

If the capabilities of COTS fusion systems cannot meet the needs of the SIHS Vision SST, then a purpose-built system could be constructed. The system developed by Fay et al. (2000) for their colour fusion study utilized two Matrox Corp. Genesis main boards and two Genesis co-processor boards, in an industrial PC rack-mount chassis, with a Pentium II host processor card. A system developed today could utilize a significantly faster processor.

If the power of a Matrox Genesis system is not required (up to 100 billion operations per second) then another approach would center on a powerful processor and COTS frame grabbers. The requirement to use an EBX or PC/104 or PC/104 Plus minimodule computer format is not believed to be required. The Vision SST fusion test bed is primarily for video and fusion image collection and will not be configured into a man portable system.

4.1.3.2.1 Frame Grabbers

A frame grabber is a board that can be plugged into a computer that will capture an analog/digital signal and digitize it so that a single frame or multiple frames can be extracted. It is a critical piece of hardware when select frames of two separate analog/digital input signals are fused. Once the frame grabber digitizes the signals and the frames are selected, they are passed to the fusion processor where it undergoes the fusion process before it is sent to the display unit. There are many different manufacturers of frame grabbers and only a select few companies are presented here. The most prevalent companies include Matrox, Sensoray, Alacron, Matrix, PixelSmart, Epix and BitFlow. Frame Grabbers are used to digitize analog/digital input signals. The application determines whether or not a frame grabber is necessary. If the application warrants that certain frames of the input signals are fused and the resulting image be evaluated then a frame grabber is necessary for this. However, if the requirement is to monitor a continuous real-time video of fused input videos than a frame grabber is not necessary. Once it is determined that a frame grabber is necessary for a certain application then all the various frame grabbers need to be evaluated so that the appropriate frame grabber can be selected.

Table 5 describes a number of frame grabbers manufactured from these companies. By no means does this include the array of frame grabbers available in the marketplace today. It is important to note that there are separate frame grabber models for different types of manufactured cameras and careful consideration is needed when selecting the appropriate frame grabber.

Frame Grabbers are used to digitize analog/digital input signals. The application determines whether or not a frame grabber is necessary. If the application warrants that certain frames of the input signals are fused and the resulting image be evaluated then a frame grabber is necessary for this. However, if the requirement is to monitor a continuous real-time video of fused input videos than a frame grabber is not necessary. Once it is determined that a frame grabber is necessary for a certain application then all the various frame grabbers need to be evaluated so that the appropriate frame grabber can be selected.

Table 5: Frame grabber results

Model	Outputs	Inputs	Resolution	Acquisition Rate
PixelSmart 512-8	Composite RGB	Multiple NTSC, PAL, LVDS, RS422	640x480, 512x480	NA
Sensoray 512	PAL or NTSC	Multiple 2 video or 4 composite	640x480 NTSC 768x576 PAL	25 – 30 frames/s
Sensoray 516	PAL or NTSC	Multiple 2 video or 4 composite	Input 704x480-NTSC/ 704x576-PAL Output 768x576-PAL/ 704x480-NTSC	25 – 30 frames/s
Alacron FFRAME-CB	Colour	1 Digital 1 Analog	NA	27 MHz
Alacron FAST-X	Not Colour	6 Digital Camera Links	NA	
Alacron FAST-UXGA	Not Colour	4 UXGA Four Analog Channels	NA	205 MHz
EPIX PIXCI-D	NO	LVDS/RS422	1Kx1K	NA
MATROX Titlemotion	VGA	NTSC-PAL	NTSC Full Frame	NA
MATROX Meteor-II	Standard and Non-Standard analog Monochrome or component RGB	NA	NA	Up to 30 MHz
MATROX Helios eA/XA	Standard and Non-Standard analog Monochrome or component RGB	NA	NA	Up to 160 MHz
MATROX Vio	HD (720p or 1080i) or SD Analog including component RGB Optional SDI	NA	NA	CCIR-601 for HD, SD

4.2 Fusion Algorithms

A literature search was conducted based on the search parameters given in Table 1. Based on the results of the literature search the following algorithms were identified for their use in image fusion: Principal Component Analysis, Discrete Wavelet Transform, Wavelet Transforms, Shift-invariant Discrete Wavelet Transforms, Laplacian Pyramid, Simple and Weighted Average, Gradient Pyramid, Contrast Pyramid, Morphological Pyramid, Ratio of Low-Pass Pyramids, Intensity-Hue-Saturation, Advanced Discrete Wavelet Transform, Edge Detection, Brovey Transform, Filter Subtract Decimate, Hermite Transform, Principal Component Analysis with Wavelet Transform, Finite Ridgelet Transform, Contourlet Transform, Dynamic Contour, Sarnoff's Feature Level, and Decision Level. These algorithms were identified through the search of approximately 40 articles and by no means include all of the available algorithms used for image fusion but do include the most prevalent algorithms in the literature.

The list of algorithms identified through literature were down selected based on times cited, availability of information, and the applicability to night vision image fusion. The selected algorithms used for this report include Principle Components Analysis, Simple Averaging, Laplacian Pyramids, Morphological Pyramids, Gradient Pyramids, Ratio of Low-Pass Pyramids, Wavelet Transforms including the Discrete Wavelet Transform and the Shift-invariant Wavelet Transform, and Edge Detection.

4.2.1 Fusion Algorithms Background

In its simplest form, an algorithm is a procedure for accomplishing a task where a given initial state will go through a set of procedures and terminate in pre-defined end-state. In the case of Image Fusion, the algorithm defines which processes the initial images go through in order to end with a fused image incorporating all of the necessary information present in the initial images.

Over the years there has been numerous image fusion algorithms developed to address the growing need for image fusion. The algorithms can be roughly divided into two groups; multiscale-decomposition (MSD)-based fusion methods, and non-multiscale-decomposition (NMSD)-based fusion methods (Blum & Liu, 2006). The basic idea of a MSD based fusion method is that a multiscale transform is performed on the source images, and then a composite multi-scale representation of these images is constructed based on a predetermined selection rule. The fused image is obtained by taking the inverse of the original multiscale transform (Blum & Liu, 2006). The most common MSD methods include pyramid transforms and wavelet transforms (WT). All NMSD are not based on multi-scale transforms. Most common NMSD fusion methods include, Principal Component Analysis (PCA), Weighted Average technique, Estimation Theory methods, and Artificial Neural Networks. Image fusion techniques can also be classified based on the level of processing where the fusion takes place. There are three main levels where image fusion may take place and they include:

- Pixel Level;
- Feature Level; and
- Decision Level.

For the purposes of this report the fusion algorithms will be classified based on the level of where the fusion processing takes place. Therefore under the classification of Pixel Level Fusion, the following algorithms will be discussed in more detail: Simple Averaging technique, PCA, Pyramid based fusion schemes, and wavelet transforms. Under the classification of Feature level fusion we will discuss the edge detection algorithm and Decision Level fusion will be briefly described but no specific algorithms will be included due to lack of literature present in the use of Decision Level fusion algorithms for the purpose of image fusion.

4.2.2 Pixel Level Image Fusion

Image fusion at the pixel level means fusion at the lowest processing level referring to the merging of the physical parameters of the source images (Pohl & Van Genderen, 1998). Among the three fusion levels, pixel level fusion is the most mature and encompasses the majority of image fusion algorithms in the literature today. Figure 20 illustrates a schematic of the pixel level fusion process.

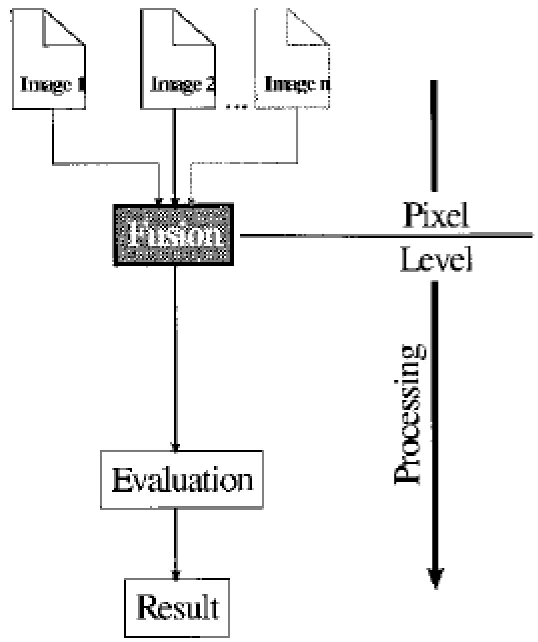

Figure 20: Schematic of Image Level Fusion (from Pohl & Van Genderen, 1998)

All input images are aligned first and then the algorithm is performed across the pixels of all the input images. Therefore, to perform pixel level fusion all input images need to be spatially registered exactly to all other input images, so that all pixel positions of all the input images correspond to the same location in the real world (Rockinger, 1996). There can be some generic requirements imposed on the fusion result from pixel level fusion:

- The fusion process should preserve all relevant information on the input imagery in the composite image (pattern conservation);
- The fusion scheme should not introduce any artefacts or inconsistencies which would distract the human observer or following processing stages; and
- The fusion scheme should be shift and rotational invariant, i.e. the fusion result should not depend on the location or orientation of an object in the input imagery. (Rockinger, 1996)

The remainder of this section will focus on the most common pixel level fusion algorithms. It will begin with a simple averaging technique, followed by principle components analysis, pyramid fusion schemes (Laplacian, Morphological, Gradient, and Contrast), and wavelet transforms (Discrete Wavelet Transform and Shift Invariant Discrete Wavelet Transform).

4.2.2.1 Simple Averaging Technique

Averaging techniques used for image fusion are the most basic and simplest techniques that are used. It works by simply taking the average intensity value of the various input images pixel by pixel (Li, Manjunath, and Mitra 1995). The averaging technique allows you to vary the weight that each input image has on the resulting fused image. Instead of having each input image contributing the same amount towards the fused image you can have one input image contributing more to the fused image based on a pre-selected rule. For instance, when fusing thermal and I² sensors you may assign larger weights for the warmer or cooler pixels of the thermal image or assign larger weights to those pixels whose intensities are much different from its neighbours (Blum & Liu, 2006). A disadvantage of the averaging technique is that if an object appears in a certain contrast from one sensor and appears in the opposite contrast in the other sensor the fusion process will effectively cancel out the object in the fused image (Fechner & Godlewski, 1995). No matter how the weighting coefficients are determined, pixels from input images with high contrast values will be depressed in the composite fused image. This is detrimental if the object of interest has a high contrast value in one of the input images. Even though, this can have negative effects with respect to target detection and recognition it is the simplest fusion scheme and is typically used as a benchmark for all other fusion schemes (Lanir, 2005).

4.2.2.2 Principal Components Analysis (PCA)

As opposed to the previous method where weighting coefficients of each input image is pre-selected, optimal weighting coefficients with respect to information content in the input images and the ability to remove redundancy in the input images, can be determined by a principal components analysis (PCA). PCA is a method of finding patterns in data of high dimensions and compressing the data into a more manageable form by reducing the number of dimensions without much loss of information (Smith, 2002). The rest of this section will provide a brief mathematical description of PCA and then it applications to image fusion, advantages and disadvantages of PCA for image fusion, followed by previous studies that have measured the effectiveness and quality of fused images using PCA.

The mathematical explanation of PCA will not go into great detail in the derivation and formulation of this method. For example, if you have a data set of two variables, the first step is to subtract the mean of each variable from all of the data points from that variable which will leave you an adjusted data set. The next step is to calculate the covariance of the two variables and place the values into a covariance matrix. If you begin with a data set of two variables you will have a 2 x 2 covariance matrix and a 3 x 3 matrix if you began with three variables. The next step is to calculate the eigenvectors and the Eigen values for your covariance. Without going into detail about eigenvectors and Eigen values, you will get a matrix with the same dimensions as your covariance matrix. The corresponding Eigen value with be in one column with each row representing the Eigen value for the corresponding column in the eigenvector matrix. For example, the Eigen value of 1.28402771 represents the Eigen value associated with the 2nd column of the eigenvector matrix.

$$eigenvalues = \begin{pmatrix} .0490833989 \\ 1.28402771 \end{pmatrix}$$

$$eigenvectors = \begin{pmatrix} -.735178656 & -.677873399 \\ .677873399 & -.735178656 \end{pmatrix}$$

The eigenvectors represent information about the patterns with the given variables. The eigenvector that is associated with highest Eigen value represents the vector in the data that provides the strongest pattern or relationship amongst the original data set. You are then able to compress your original data set by choosing the eigenvector with the highest Eigen value, which is known as the principle component. If you had a data set of 20 variables you would be able to compress it to 15 variables by choosing the highest 15 Eigen values. To get to final data set you would multiply the transpose of the eigenvector by the transpose of the original data set. This will give the original data in terms of vectors and these vectors describe the patterns within the data set. The whole process of PCA is to transform the data so it can be expressed in terms of patterns and decompose the data into vectors that describe the greatest contribution to the patterns within the data set.

This relates to image fusion because each image can be seen as a variable in a data set. For two images with N x M pixels you will have a NM matrix with 2 dimensions with each vector containing the intensity level from the same pixel from each individual picture. A PCA is then performed on this data set and the highest Eigen value is selected in order to compress the data into a single dimension. Instead of subtracting the mean of each input image from the image, each input image is filtered and those filtered images are subtracted from the original images (Chari, Fanning, Salem, Robinson, and Halford 2005). The first eigenvector usually contains more than 90% of the information present in all of the original images (Senthil & Muttan, 2006). The picture will be of less quality than any of the originals because you are only selecting the highest Eigen value and therefore some of the patterns between the original images are lost (Smith, 2002). In order for PCA to be used effectively there needs to be a strong correlation between the original image data and the fused image data, and sometimes this is not the case (Huihui, Lei, and Hang, 2005).

The main advantage of PCA is that you are able to have a large number of inputs and that most of the information within all the inputs can be compressed into a much smaller amount of outputs without much loss of information (Senthil & Muttan, 2006). One disadvantage of the use of PCA for image fusion is that you are selecting only the first eigenvector to describe your data set. Even though this eigenvector contains 90% of the shared information there is still some information that will not be evident in the final fused image.

PCA performs well when compared to other image fusion algorithms. In a study by Tsagaris and Anastassopoulos (2006), PCA was superior to the simple averaging technique and the Morphological pyramid algorithm for the majority of the measures and only being inferior to the discrete wavelet transform. In a study that measured detection of various targets, PCA was superior to the simple averaging and edge detection methods and also performed favourably when target detection time was taken into consideration.

4.2.3 Pyramid Based Fusion Schemes

All pyramid based fusion schemes follow the same basic process. An image pyramid can be described as a sequence of images where each image is constructed by low or band-pass filtering the previous image and reducing its sample density (Zheng, Essock, and Hansen, 2005). Typically, the reduction in sample density is by a factor of 2 so that each successive image representation is halved in both spatial densities (Rockinger, 1998). The fused image is derived by using a pre-determined selection rule for each level of the pyramid. Once a fused pyramid representation is developed the inverse function of the pyramid transform will produce the fused image (Zheng et al. 2005). The method used to filter the original images and reconstruct the fused image from the pyramid levels will define the specific type of pyramid based fusion scheme. Figure 21 illustrates the successive levels of a pyramid based fusion method of a single input image. At each level of the pyramid the image is down-sampled and specific frequencies are filtered out from the previous image.

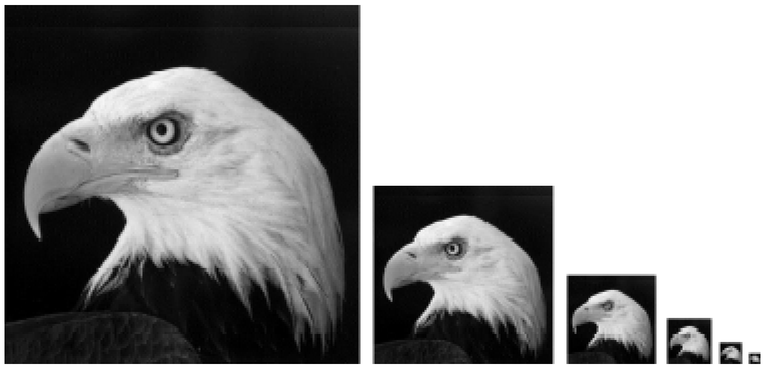

Figure 21: Successive Levels of an Image using a Pyramid Based Method

4.2.3.1 Laplacian Pyramid Algorithm (LAP)

The Laplacian Pyramid Algorithm (LAP) is the most frequently studied version of the pyramid transform (Blum & Liu, 2006). Each level of the LAP is constructed from its lower level by four basic procedures:

- Blurring (low-pass filtering);
- Sub-sampling (reduce size);
- Interpolation (expand in size); and
- Differencing (subtract two images pixel by pixel (Blum, 2006)).

The down-sampling of the image is by a factor of 2, which means keeping one sample out of every 2, for both the horizontal and vertical directions (Blum & Liu, 2006). This down-sampling can be achieved due to the reduction in the spatial frequency content due to the low-pass filtering (Toet, 1989). The up-sampling procedure inserts a zero into every other sample in both the horizontal and vertical directions. After the differencing procedure, the resulting image is a band-pass filtered copy of its predecessor (Sadjadi, 2005).

Once the pyramids are constructed for each input image a selection method is used to decide from which source what pixels are used to contribute at each level of the pyramid (Sadjadi, 2005). A common method is the selecting the source which has the highest contrast feature for inclusion into the fused image (Bender, Reese, and van der Wal, 2003). The inverse pyramid transform merges all the collected features from the input images into a single coherent image (Bender et al. 2003). Due to the fact that this rule selects the input image with the highest contrast this method enables generally higher image contrast (Bender et al. 2003).

LAP performs favourably when compared to other fusion methods including other pyramid methods. With respect to entropy, image quality index, and spatial frequency, LAP ranked higher than 4 other pyramid based methods when fusing night time imagery where brightness and contrast where very different between input images (Zheng et al. 2005). Using the same metrics and with input images with similar brightness and contrast the LAP finished 2nd amongst the pyramid based fusion methods behind the Contrast method, which will be discussed later (Zheng et al. 2005). A group of human observers found that the LAP method was the preferred method of fusion, with the Shift Invariant Discrete Wavelet Transform, when examining night vision images (Chen & Blum, 2005). This study looked at 17 different fusion algorithms and along with the subjective tests the LAP finished in the top 3 of 4 out of the 7 objective tests (Chen & Blum, 2005).

A disadvantage of the LAP is the fact that it only decomposes images by a factor of 2, which results in certain amount of restriction during the composition of the fused image (Jishuang & Chao, 2001). Increasing the decomposition levels, by methods not restricted by the factor of 2, will drastically increase the computational demand but improve the quality of the fused image (Jishuang & Chao, 2001). Image fusion methods based on local contrast decomposition do not distinguish between material edges and temperature edges which could cause an abundance of irrelevant information even though there is an enhancement of all the details in the scene (Toet & Franken, 2003). The addition of irrelevant information may clutter the scene and lead to misinterpretation of perceived detail (Toet & Franken, 2003).

4.2.3.2 Morphological Pyramid Algorithm (MORPH)

Normal filtering techniques, as in the LAP, usually alters the details of shape and the exact location of the objects in the image (Sadjadi, 2005). Morphological pyramid algorithms (MORPH) address this issue by removing image details without any negative effects or without adding any gray scale bias (Toet, 1989). The main difference between the MORPH and the LAP is the use of morphological pyramids, based on a different filtering method, instead of Laplacian pyramids with simple low-pass and band-pass filters it uses a filtering method that relies on shape definition, extraction, and definition (Sadjadi, 2005).

Morphological filters are sequences of morphological operations that have special properties with respect to shapes in the image (Toet, 1989). They can be used to 'clean-up' gray scale images by choosing a structuring element that is larger than the unwanted details in the image (Ramac, Uner, and Varshney, 1998). Morphological filters use what is called opening and closing transformations. These transformations are dual operations, in that what one does to the image foreground the other does to the image background (Toet, 1989). Sequentially alternating these transformations means that the background and foreground are treated in the same way (Toet, 1989). Morphological filters can also extract objects of a certain size range from an image (Ramac et al. 1998).

Once filtered, a morphological pyramid can be formed by a specific sampling method. This process is similar to the LAP. Once the pyramids are formed a selection rule is applied and a composite image is formed. The fused image is developed by the inverse pyramid transform.

The non-linear filtering method used in MORPH was thought to improve performance of linear filters (e.g. LAP). Based on the work by Zheng et al. (2005), the MORPH method actually does not perform as well as the LAP method in terms of the subjective tests performed (Entropy, Image Quality Index, and Spatial Frequency) for both the night vision images and the day time images. These results were verified in the work by Chen and Blum (2005); however results based on image entropy found no correlation to subjective scores from human observers. A reason that the MORPH method may score high in the subjective tests is that these measures are sensitive to increases in contrast levels and is sensitive to noise and other dramatic fluctuations in the image that may be caused by artefacts and algorithm created spots (Chen & Blum, 2005). The MORPH method has also proved inferior in other subjective fusion tests when compared to non-pyramid based fusion methods. With respect to the Image Fusion Performance Measure (IFPM), the MORPH method performed poorly when compared to the PCA method, the discrete wavelet transform, and the simple averaging technique (Tsagaris and Anastassopoulos, 2006).

4.2.3.3 Gradient Pyramid Algorithm (GRAD)

The Gradient Pyramid Algorithm (GRAD) is similar to the other pyramid methods. The difference between this and the LAP method is that a gradient operator is applied to every level of the pyramid producing horizontal, vertical, and 2 diagonal pyramid sets for each pyramid level (See Figure 22), as compared to just horizontal and vertical pyramid sets in the LAP method (Zheng, Essock, and Hansen 2004). The rest of the GRAD follows similar steps as the other pyramid based methods. Once the pyramid sets are developed, a certain selection and match criteria is enforced for the source images, based on the results of the selection and match process a composite image is obtained, and the inverse pyramid transform will produce the fused image (Wang, Zhang, Wang, and Wang, 2005). However, due to the fact there are more pyramid sets associated with the GRAD there are several intermediate steps that are taken to prepare the composite image for fusion.

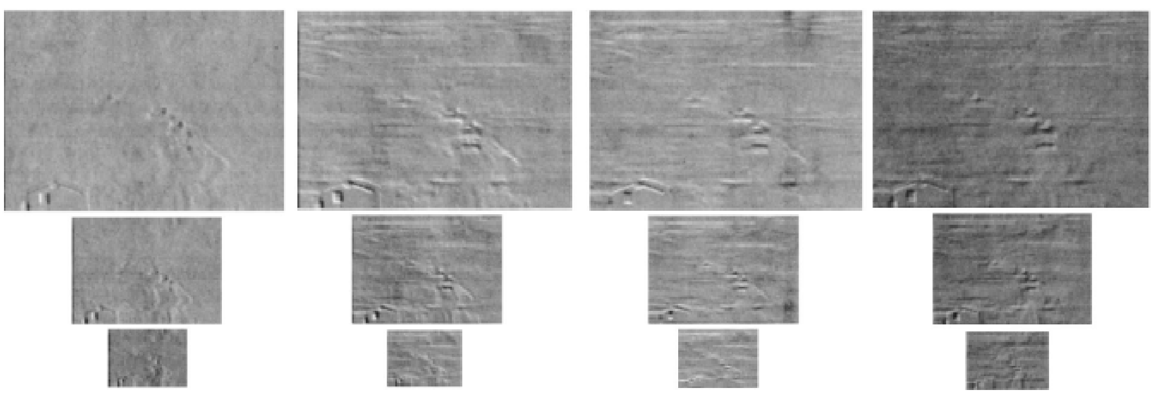

Figure 22: Four Levels of the GRAD Pyramid Set (from Sims & Phillips, 1997)

Before the inverse pyramid transform is performed to compose the final fused image the 4 gradient pyramids need to be converted into Laplacian pyramids. This occurs over several steps. The first step is to convert each gradient pyramid level to a corresponding second derivative pyramid. These pyramids are then summed to form a filter subtract decimate (FSD) Laplacian pyramid. The FSD Laplacian pyramid can then be converted to a composite Laplacian pyramid which then can compose the fused image through an inverse pyramid transform (Sims & Phillips, 1997).

One advantage that the GRAD has over the LAP is that it has an improved temporal stability, indicated by a reduced conditional entropy measure (Rockinger, 1998). The improved temporal stability comes at a cost of visual clarity when identifying targets (Sims & Phillips, 1997); and sharpness, when compared to the LAP (Miao & Wang, 2006). The GRAD also has the advantage of transferring a greater amount of salient information from the input image to the fused image when compared to the MORPH method but not as much as the LAP (Chen & Blum, 2005).

4.2.3.4 Ratio of Low-Pass Pyramid Algorithm (RoLP)

The Ratio of low pass pyramid algorithm (RoLP) judges the relative importance of pattern segments based on their local luminance contrast values (Toet, 1989). All input images are decomposed into light and dark blobs on decreasing levels of resolution (pyramids). The image at each level of the pyramid is essentially the ratio of the two successive levels of the Gaussian pyramid (Sims & Phillips, 1997). The composite image is formed by selecting at each pixel location and pyramid level the largest deviation of contrast compared to the input images (Sadjadi, 2005). These pixels are used to form the composite image. The fused image is formed by the same expand and add procedure used in the LAP (Sims & Phillips, 1997). Originally, the RoLP was explicitly intended for use by human observers (Zheng et al. 2005). Toet, (1989), claims that the LAP is not a faithful representation of the human visual system because it only accounts for absolute luminance differences whereas the RoLP encodes absolute luminance contrasts.

In objective performance measures the RoLP performs similar to the LAP with respect to Image Entropy and Spatial Frequency (Zheng et al. 2004). Both these methods have almost Image Quality Indices which is a measure for images without a ground truth reference (Zheng et al. 2004). However, a similar study was performed a year later by the same group and they found that the RoLP was inferior to the LAP, GRAD, and MORPH methods. This outlines the significant concern over the validity of objective measures used to measure the quality of image fusion. The RoLP does receive favourable results with respect to image entropy but drastically inferior to the LAP and GRAD with respect to the sharpness of the image (Miao & Wang, 2006). The RoLP is known to produce algorithm-created spots in the fused image that will affect the quality of the image - See Figure 23 (Chen & Blum, 2005). The RoLP may receive favourable results from the entropy measure because entropy is sensitive to dramatic fluctuations in the image but yet cannot discern the fluctuations to being from either noise or useful information (Chen & Blum, 2005). As you can see from Figure 23, the RoLP may produce unwanted noise in the fused image.

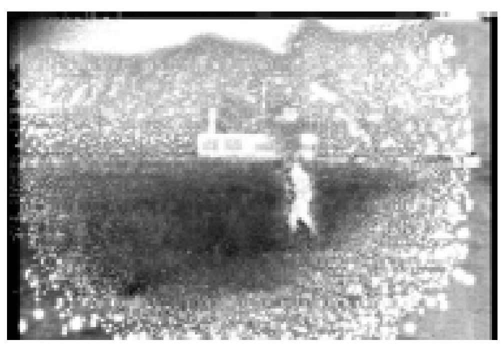

Figure 23: Fused Image from RoLP Method

4.2.4 Wavelet Transforms (WT)

Wavelet transforms are very similar to pyramid-based methods meaning that the transformed (decomposed) images are combined in the transform domain using a defined fusion rule. Then the composite image is transformed back into the spatial domain to give the resulting fused image (Hill, Canagarajah, and Bull, 2002). The basic idea of the wavelet transform is to represent an image as a superposition of wavelets, with each wavelet having an assigned wavelet transform value. This is very similar to the Fourier transform in signal processing where any signal can be broken down into a series of sine waves of different frequencies, with each frequency having an assigned power (contribution) to the overall signal. When the wavelet transforms of the images are computed they contain low-high, high-low and high-high frequency bands of the image at the different levels while the low-low band of the image is at its coarsest level. The low-low band transform values are all positive values while the other bands contain values that fluctuate around zero. The larger absolute transform values represent to sharper brightness changes that may identify edges, lines, and regional boundaries (Li et al. 1995). Similar to the pyramid-based methods a selection rule is put in place to select the transform values at each pixel level and the inverse wavelet transform will produce the fused image based on the combined transform coefficients (Li et al. 1995). The transform coefficients are the result of the low and high-pass filters, and the down-sampling the image goes through. The result of the low-pass filter produces approximation coefficients while the result of the high-pass filter produces detail coefficients - See Figure 24 for a schematic for the basic fusion scheme of the wavelet transform.

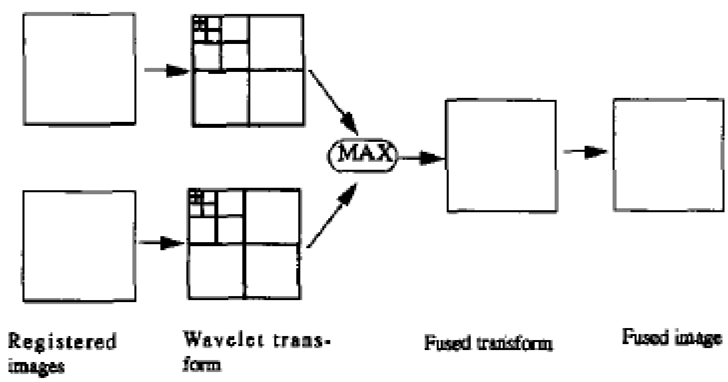

Figure 24: Schematic for the Basic Wavelet Transform Fusion Scheme

The two most common versions of the wavelet transform are the Discrete Wavelet Transform (DWT0, which yields a shift-variant signal representation, and the Shift-invariant Discrete Wavelet Transform (SiDWT), which combats the shifting signal representation (Piella & Heijmans, 2002). Wavelet transforms have a number of advantages over pyramid based methods. While pyramid based methods produce an over-complete signal representation, the wavelet transform results in a non-redundant signal representation (Rockinger & Fechner, 1998). This means that at different levels of a pyramid may contain the same information while at each levels of the wavelet transform the information is unique.

The wavelet transform has certain advantages over pyramid-based fusion algorithms:

- The size of the wavelet transform is the same as the image, even when the image height and weight are not powers of 2. The Laplacian pyramid is 4/3 the size of the image proving that the wavelet transform is more compact;
- The wavelet transform provides directional information in the high-low, low-high, and high-high frequency bands, while the pyramid-based techniques fail to introduce any spatial orientation selectivity into the decomposition process;
- The information contained at different resolution is unique while the pyramid decomposition contains redundancy between different scales; and

- In the Laplacian pyramid-based fusion, often the fused images contain blocking effects in the regions where the multi-sensor data are significantly different. This can be attributed to the instability in the reconstruction from the fused coefficients when the two sensor data differ significantly.

  (Li et al. 1995)

4.2.4.1 Discrete Wavelet Transform (DWT)

The Discrete Wavelet Transform (DWT) is obtained most frequently by using the Mallat Algorithm. In image processing, the Mallat algorithm constructs a scaling function and three wavelet functions. The scaling function produces an image approximation of the low frequency information, while the wavelet functions produce high-low, low-high, and high-high images that constitute the wavelet coefficients (Huihui et al. 2005).

Using the Mallat algorithm an input signal is both high-pass filtered and low-pass filtered and down-sampled by a factor of 2. The result of the high-pass filter produces detail coefficients while the result of the low-pass filter produces the approximation coefficients - See Figure 25. The approximation coefficients are then low and high-pass filtered and down-sampled to produce a new set of approximation and detail coefficients. These steps continue until the terminal node - See Figure 26. Once the terminal node is reached, one method of fusing the image is by choosing the average of the approximation coefficients at the highest transform scale and the largest absolute value of the detail coefficients at each transform scale (Zheng et al. 2005). Due to the fact that different rules are applied to the low and high frequency portions of the signal a better fused image is thought to be the result (Jishuang & Chao, 2001). Once the coefficients are selected the inverse of the Mallat algorithm is performed to obtain the fused image.

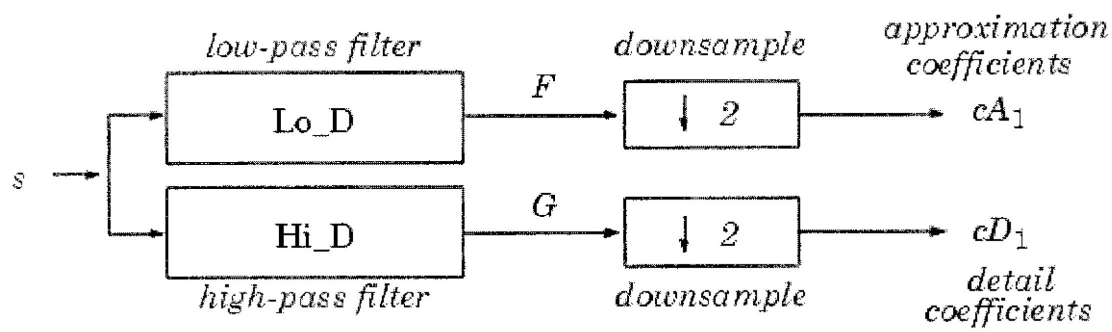

Figure 25: Schematic of Mallat Algorithm Decomposition Process

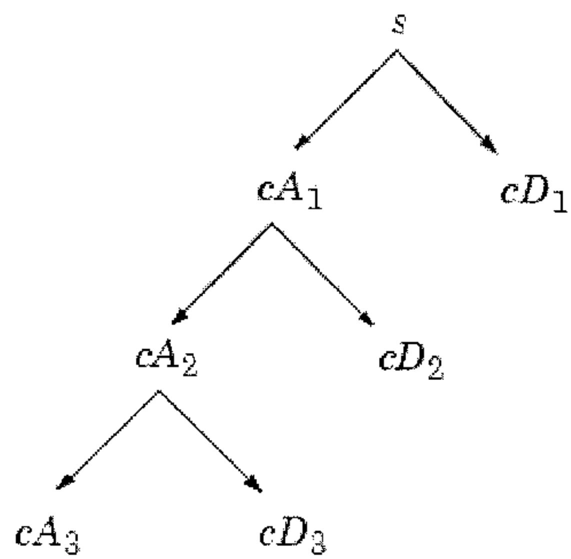

Figure 26: Tree Schematic of Obtaining Approximation and Detail Coefficients using the Mallat Algorithm

The DWT using the Mallat algorithm does introduce some problems:

- This transform is not shift-invariance which can easily introduce artefacts in the fusion process, such as ringing and aliasing. This is due to the down-sampling and up-sampling by the factor of in the decomposition and reconstruction. Up-sampling makes the frequency-time space uncertain. The wavelet coefficients may change dramatically for minor shifts of the input signal and the energy distribution may change dramatically as well at the different resolution levels, which may distort the result of the reconstruction.
- Pixel by pixel analysis is not possible since data is reduced at each resolution; it is then not possible to follow the evolution of a dominant feature through the different levels.
- The images are decomposed with sizes that are powers of two; because the resolution is reduced by two at each level it is not possible to fuse images of any sizes.

(Huihui et al. 2005)

The main disadvantage of the DWT is it shift-invariance. Despite these problems the DWT still performs favourably when compared to other fusion methods. According to observers in the Chen and Blum study (2005), the Shift-Invariant Discrete Wavelet Transform and the LAP generally outperformed all other fusion methods while the DWT and GRAD methods were the next best methods. These results were similar in the quantitative measures of this study where the DWT performed similar to the GRAD pyramid method but not as well as the LAP and the Shift-Invariant Discrete Wavelet Transform (Chen & Blum, 2005). These results were similar to that of Zheng et al. (2005) where the DWT performed similar to the GRAD method but not as well as the LAP when fusing night vision imagery. Even though the DWT is more compact and contains non-redundant information it still has a major drawback of not being shift-invariant.

4.2.4.2 Shift-Invariant Discrete Wavelet Transform (SiDWT)

The Shift-Invariant Discrete Wavelet Transform (SiDWT) is an extension to the DWT but uses different algorithms and approaches to improve the temporal stability and consistency of the fused image to yield better results. There are several ways to produce a shift-invariant version of the DWT. One simple way is to eliminate the down-sampling feature of the DWT. This is very inefficient method of creating a SiDWT but it is simple and effective (Chari et al. 2005).

Another common method of producing a SiDWT is by using the á trous algorithm. The á trous algorithm is an undecimated dyadic wavelet transform that is suitable for signal and image processing because it is isotropic and does not introduce any artefacts (Wang, Ziou, Armenakis, Li, and Li, 2005). The á trous uses a different formula and avoids the use of the down-sampling and up-sampling procedures as compared to the Mallat algorithm to obtain its coefficients. However, the coefficients still contain magnitude information and the importance of the local features (Huihui et al. 2005). The á trous algorithm has several advantages over the DWT:

- Wavelet and approximation planes have the same dimensions as the original image, which avoids the introduction of artefacts because of the lack of up-sampling and down-sampling;
- Unlike the DWT, there is redundancy of information at each scale, allowing the better detection of a dominant feature; and
- Can be applied to any sized images for fusion.

(Huihui et al. 2005).

The advantages of the á trous algorithm come at the cost of computational and time demands (Huihui et al. 2005). Other algorithms used to produce a SiDWT are the Haar wavelet and the Daubechies wavelet.

Obtaining the fused image by the inverse SiDWT is similar to the DWT except for the omission of the up-sampling step due to the removal of the down-sampling step in the decomposition phase (Chari et al. 2005).

For image fusion purposes, the SiDWT generally outperforms all other methods previously discussed. In terms of subjective results the SiDWT and the LAP outperformed all other methods and placed in the top 3 of 7 objective measures 4 times which also ranked the highest along with the LAP method (Chen & Blum, 2005). In terms of sharpness and entropy, SiDWT performs better than most of the pyramid based schemes except for the LAP (Qiguang & Boashu, 2006). SiDWT outperformed all DWT based methods when a ground truth image was obtained using a cut and paste method (Hill et al. 2002). These results demonstrate the importance of shift-invariance in wavelet transform fusion in terms of producing clear fused images free of any additional artefacts.

4.2.5 Feature Level Image Fusion

Feature level methods are the next stage of processing where image fusion may take place. Fusion at the feature level requires extraction of objects (features) from the input images (Pohl & Van Genderen 1998). These features are then are then combined with the similar features present in the other input images through a pre-determined selection process to form the final fused image. Since, one of the essential goals of fusion is to preserve the image features, feature level methods have the ability to yield subjectively better fused images than pixel based techniques (Samadzadegan, 2004). A schematic of feature level fusion is shown in Figure 27 adapted from Samadzadegan, 2004.

Common algorithms that fuse images at the feature level include edge detection methods and artificial neural networks. For our purposes only the edge detection method will be discussed in greater detail.

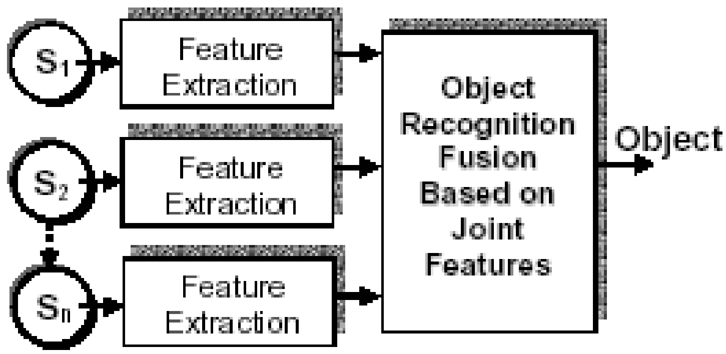

Figure 27: Schematic of Feature Level Fusion

4.2.5.1 Edge Detection Method

The goal of the edge detection method is to identify changes, based on contrast, of the input images that are likely to identify important events or targets in the real world image. Since the edges of objects present in the images are most likely to display these changes in image intensity and are preserved in most cases, contours are often used to fuse images from different sensors (Liu, Zhou, and Wang, 2006). Edge Detection Methods use specific filters to extract edge information of each band (Lanir, 2005). Depending on the filter used, specific features such as lineament, edge, texture, and gray degree will be segmented from the input image (Rui & Ming, 2006). Edge detection methods can fuse images by first selecting an input image as the base image and then overlaying the extracted features onto the base image (Lanir, 2005). Another method is to calculate specific features from all input images and then use a pre-determined selection rule to extract certain features from certain input images to obtain the final fused image. Since edge detection methods do not work on the pixel by pixel basis like the previous algorithms, features are calculated by using windows of pixels which contain the pixel of interest and its neighbouring pixels (Kwon Der, and Nasrabadi, 2002). Specific features such as, local-maximum gray level, local contrast, local-average gradient strength, and local variation have been used in the past (Kwon et al. 2002). This type of edge detection method is known as a search-based method where edges are detected based on search criteria that look for maxima and minima values (Siddique & Barner, 2002). Due to the fact that changes in intensity values of a object is likely to occur over a number of pixels, edge detection algorithms usually take the 1st derivative of the input image in order to measure the where the change in pixel intensity is the highest. Other methods that are zero-crossing based, take the 2nd derivative of the input image where the point at which it crosses zero indicates where the rate of change in pixel intensity is the highest (Siddique & Barner, 2002).

An important factor in edge detection is applying the right threshold to the derivative function where you believe that an edge will be present. Selecting a threshold to small will identify many edges while a threshold to large may miss some important edges. Another critical step in image fusion using the edge detection method is to select the appropriate size of window where the specific features are extracted. If the size of the window is too small then they will be a lot of ambiguity and the target will not be properly extracted and if the window is too large then there will not be enough overlap to enhance the identification of the target (Lanir, 2005).

The search-based and zero-crossing based edge detection methods are more classical methods and are single resolution. However, significant intensity changes can occur at different resolution levels. Therefore, single resolution is unlikely to be sufficient in many applications (Siddique & Barner, 2002).

There are several Multi-resolution (MR) edge detection methods that work very similar to the pyramid and wavelet methods described earlier. A MR edge detection method will generate a series of progressively lower resolution images with fewer details (Siddique & Barner, 2002). All MR edge detection methods can be classified as either linear or non-linear. Linear methods are likely to blur important image features at each decomposition level while failing to remove small scale detail (Siddique & Barner, 2002). Non-linear methods have the ability to preserve large-scale edges while completely removing structures smaller than a specified window size (Siddique & Barner, 2002). Choosing a window size that is too small is susceptible to noise contamination while choosing a window size that is large may be robust to noise contamination it may not detect finer details.

The Department of Electrical Engineering and Computer Science from Lehigh University describes a MR method incorporating edge detection and wavelet coefficients. Firstly, an edge detection algorithm is applied to the low-low bands at each wavelet level. The results of the edge images provide information on the location and intensity of edges in the source images. Using the edge information the source images are segmented into regions with each region obtaining a certain activity level based on the average of the high-frequency wavelet coefficients. The larger the activity level in a region indicates the more informative the region is. Once the activity levels of the regions are obtained specified fusion rules are applied to obtain the final fused image Examples of the fusion rules are:

- High activity regions are preferred over low activity level regions;
- Edge points are preferred over non-edge points;
- Small regions preferred over large regions;
- Avoid isolated points in decision map.

Based on the pre-selected rules the fused wavelet coefficient image is obtained and by the inverse wavelet transform the final image is obtained.

Edge detection methods can be beneficial but the threshold level and window size needs to be tailored to each individual application. This may not be suitable for all applications. The edge detection method did not perform well compared to the PCA and the simple averaging technique in target detection tasks. It had significantly less detection rates and rated poor in the subjective opinion of the observers (Lanir, 2005).

4.2.6 Decision Level Image Fusion

Decision Level methods are at the highest level of processing where image fusion can take place. Fusion at the Decision Level takes Feature Level fusion one step further by declaring identities to the objects recognized, by the individual input images, and then assigning a quality measure to the extracted features - See Figure 28. The obtained information is then combined by applying decision rules to reinforce common interpretation and resolve differences of the observed objects (Pohl & Van Genderen 1998).

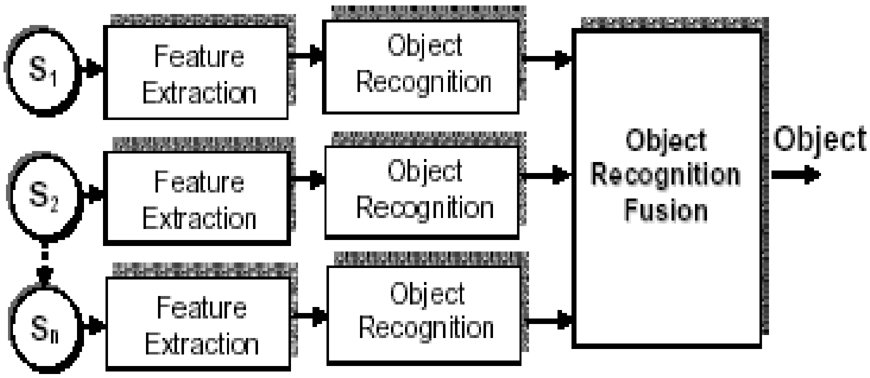

Figure 28: Schematic of Decision Level Fusion (adapted from Sarmadzadegan, 2004)

Due to fact that decision level fusion methods rely on the object recognition by all sensors in order to produce a valid representation of the input images, if an object is not recognized by all the sensors (via input images) then the output image will not utilize the full benefits of image fusion (Gunatilaka & Baertlein, 2001). Decision level fusion also creates another source of possible error when compared to the other fusion levels. If there is an error in recognition of objects from one of the sensors this error will be transferred to the output fused image. Some common algorithms used in decision level fusion include Dempster-Shafer Theory, Fuzzy Logic, Rule-based Fusion, and Bayesian Networks. Based on the high computational demands and the drawback of every sensor needed to recognize the objects in an image to provide a valid representation of the scene no decision level fusion methods will be discussed in detail.

4.3 Evaluation Metrics

A preliminary search was conducted to identify fusion articles which contained references to image fusion performance, image fusion evaluation or image fusion measurement. This initial search identified approximately 7,640,000 articles! The search was refined to identify specific articles that only included one modifier (performance, evaluation or measurement). Image fusion and performance resulted in 1,560,000 hits; image fusion and evaluation resulted in 1,310,000 hits and image fusion measurement resulted in 1,160,000 articles. Using the term “metrics” and “image fusion” resulted in the detection of 974,000 articles.

A refined literature search literature search was then conducted to identify articles which contained the exact key phrase terms. This search identified a total of 88 articles that included the exact term “image fusion evaluation” and a total of 462 reports that included the exact term ‘image fusion measurement”. In an effort to refine the search, the key phrases were modified with the terms “objective” and “subjective”. Combining the term “objective” with “image fusion evaluation” yielded only four results while “subjective image fusion evaluation” yielded seven results. Adding the term subjective or objective to “image fusion measurement” yielded zero results. A refined literature search literature search was also conducted to identify articles which contained the exact key phrase “image fusion analysis”. This search identified a total of 121 articles.

A review of the search results identified a number of medical references pertaining to the analysis of medical images, i.e. Image fusion analysis of [99m]Tc-HYNIC-octreotide scintigraphy and CT/MRI in patients with thyroid-associated orbitopathy: and the importance of the lacrimal gland (Kainz, Bale, Donnemiller, Gabriel, Kovacs, Decristoforo, and Moncayo, 2003). Refining the search to eliminate specific medical applications only reduced the number of articles marginally.

Based on a review of article titles and abstracts approximately 40 articles were selected and obtained for detailed examination. A review of these articles identified additional references for review. Approximately 70 articles were retrieved and reviewed during this study.

A discussion on the results of the literature review on image fusion metrics is detailed below. The image fusion metric results are organized into the following sections: introduction, subjective evaluation approaches, objective evaluation approaches and suggestions on how the SIHS TD should investigate fusion performance.

4.3.1 Evaluation Criteria

The ultimate aim of image fusion is to create a faithful and composite image that retains the important information from the source images while minimizing the noise caused by fusing the images. For the SIHS application, these images will be typically viewed and interpreted (perceived) by an operator. A number of evaluation approaches and metrics have been proposed to quantify and qualify image fusion performance:

- The fusion measure must be able to identify and localize visual information in the input and fused images (Petrović & Xydes 2005).
- The fusion process should preserve all relevant information of the input imagery in the composite image (Petrović & Xydes 2005). Conversely the fusion metric must be able to identify losses in relevant information.
- The fusion scheme should not introduce any artefacts or inconsistencies that would distract the human observer or disrupt subsequent processing stages (Petrović & Xydes 2005). Conversely the fusion metric must be able to identify artefacts or inconsistencies added to the fusion image.
- The fusion measure must be able to evaluate perceptual importance (Petrović & Xydes 2005).
- The fusion measure must be able to measure the accuracy with which input information is represented in the fused image (Petrović & Xydes 2005).
- The fusion measure must be able to distinguish between true scene information and artefacts caused by the fusion process (Petrović & Xydes 2005).
- For video sequences, the fusion measure must have temporal consistency, in that the gray level changes in the input sequence must be present in the fused sequence without delay or contrast (Rockinger & Fechner, 1998). Temporal inconsistencies of fusion systems can arise due to asynchronous operation of the sensors (i.e. cameras may not be capturing images at the same rate or at consistent intervals).
- The fusion measure must have temporal stability. In that test and retest results must be comparable (Rockinger & Fechner, 1998)

- The fusion process should be shift and rotation invariant. The fusion results should not depend on the location or orientation of the object. (Rockinger & Fechner, 1998)

4.3.2 Subjective Evaluation Approaches

Fusion performance has been investigated using subjective and objective approaches. Since human perception of the composite image is of paramount importance, a number of investigators have used subjective or human in the loop evaluation methods. The subjective approaches use well established scientific methods adapted for video and still image quality assessment (Wang, Sheik and Bovik, 2003). Subjective evaluation approaches were utilized in the image assessment of compression algorithms, noise reduction, image quality, etc. Image quality in itself does not reveal how well human performance will be affected, i.e. a subject may perform best with a lower resolution but clean image versus a higher resolution but noisy image (Wang, et al).

Two basic subjective evaluation approaches were noted in the literature, active or task related (quantitative) and descriptive (qualitative). Quantitative approaches were utilized by Toet and Ijspeert (2001), where subjects assessed different fusion approaches on target detection and recognition, as well as subject perception of situational awareness. Ryan and Tinkler (1995) evaluated the potential advantage of fusion for helicopter pilots in real and simulated flight. Dixon, Canga, Noyes, Troscianko, Nikolo and Bull (2006) completed a target detection task evaluating different fusion algorithms and image compression methods.

In addition to quantitative subjective tests, a large number of qualitative evaluations have been undertaken to rate or rank the quality of fusion images. Lanir (2005) evaluated both target detection performance and fused image quality generated from four fusion approaches. Petrović and Xydeas (2005) ranked subject preference for eight different fusion schemes. Subjective evaluation approaches will be described in greater detail the following section.

While subjective evaluations are the most reliable, credible and direct method to evaluate fusion performance they are difficult to control, expensive and time consuming. Concerns raised in the literature with subjective fusion evaluations are summarized below:

- Results are task (detection, recognition, identification, and situational awareness) and environment dependent;
- Results vary according to target characteristics;
- Results are complicated by observer vision ability (acuity, contrast sensitivity, colour deficiency, etc.);
- The size and composition of the test audience (novice versus expert) affects the results;
- Maturation by the subjects - processes within the participants as a function of the passage of time (not specific to particular events), e.g., growing older, hungrier, more tired, and so on;
- Inherent personality preferences may affect results, i.e. sensing people, in accordance with the Myers-Briggs Type Indicator (MBTI), tend to focus on the present and on concrete information gained from their senses while intuitives tend to focus on the future, with a view toward patterns and possibilities. These people prefer to receive data from the subconscious, or seeing relationships via insights
- Reliability within subject assessments is poor, i.e. there is a need to realign individual scales if multiple sessions are required;
- Repeatability in experiments is difficult due to variations in image sources;
    - Ambiguous light levels;

- Signal intensities;
  - Contrast;
  - Noise;
  - Intrinsic image characteristics (i.e. gray scale images vs. colour);
- Differences in field of view;
- Differences in refresh rates; and
- Differences in display performance.

4.3.2.1 Quantitative Subjective Evaluation

Quantitative fusion assessment has focused on the target detection, recognition and situational awareness. Target detection and recognition assessment has been assessed in naturalistic and in laboratory settings. By their nature, real time assessments are difficult to duplicate, instead most fusion assessment experiments have focused on the capture of still or live video of targets in operational settings. The fusion community has captured and shared a number of multi-spectra reference images for algorithm development and assessment. These images are then used in psychophysical testing in a laboratory setting. Patches displaying just the target in question (Essock, Sinai, McCarley, Krebs and DeFord, 1999) and full screen images – see Figure 30 have been used in psychophysical tests. Short clips of video images have been used in fusion assessment. Video length reported in the literature varied between 100 frames (Rockinger & Fechner, 1998) and complete missions (Ryan & Tinkler, 1995). In addition to the assessment of fusion performance through live video, individual video frames or stills have been used to assess objective fusion performance. The objective performance of the fusion system is determined by averaging individual frame results across the entire clip.

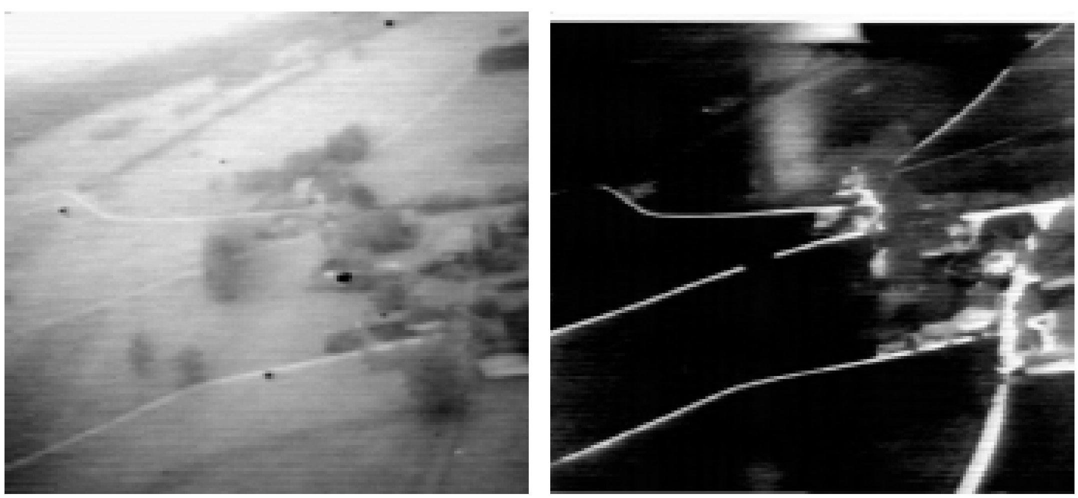

Figure 29: Video sample - low light TV image (left); forward looking infrared image (right) from Rockinger and Fechner (1998)

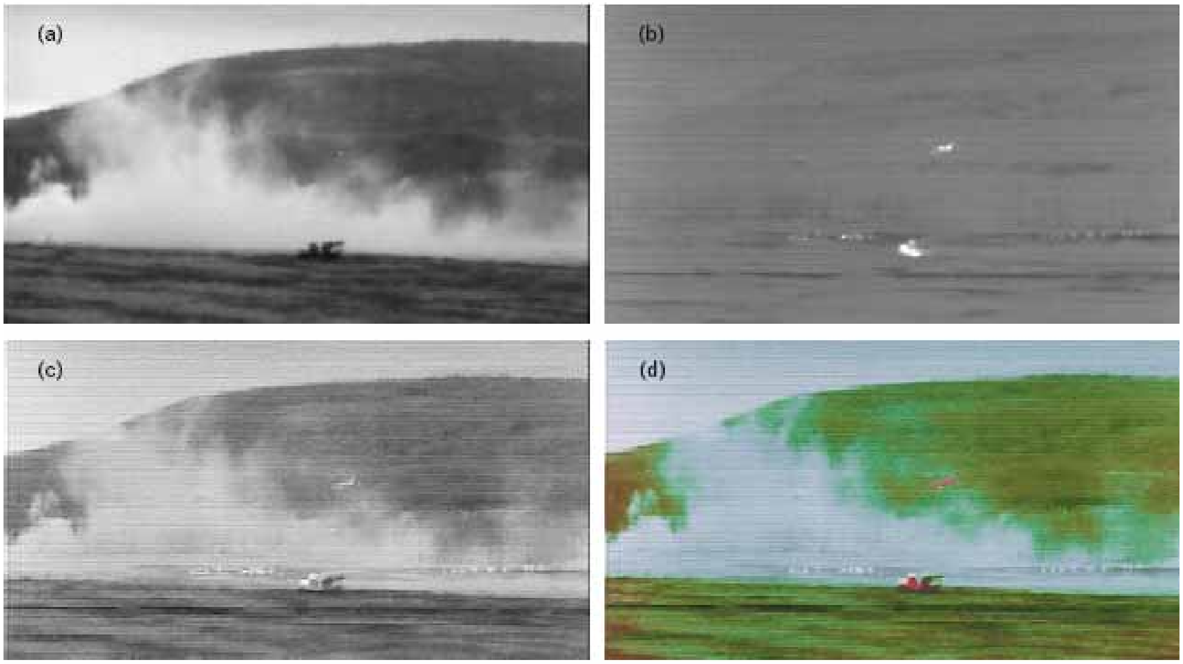

Figure 30: Image samples- smokescreen penetration and target pop-out is achieved through the color fusion of visible CCD and FLIR imagery in this daytime scene.

Figure 30shows imagery provided through the Canadian Defence Research Establishment, Valcartier, Québec, as part of a NATO study (a) Intensified visible image; (b) Thermal IR (FLIR) image; (c) Gray fused image; and (d) Color fused image. (Waxman, Aguilar, Fay, Ireland, Racamato, Ross, Carrick, Gove, Seibert, Savoye, Reich, Burke, McGonagle, and Craig, 1998)

Imagery used for target detection or scene detail assessment have included personnel, vehicles, aircraft, buildings, and ground features (water, roads, trails, etc.). Unfortunately except for a few studies environmental conditions, lumination, target detection distances, temperature and target sizes or temperature differences (where appropriate) were not described in sufficient detail in the literature reviewed.

4.3.2.1.1 Target Detection, Recognition and Identification Assessment

Experiments were performed by investigators that assessed the perception of "details" or the "detection" of object classes in an image. Toet and Franken (2003) assessed individual performance in their ability to detect the following classes of objects through a variety of fusion approaches:

- Building;
- Person;
- Road or path;
- Fluid water (e.g. a ditch, a lake, a pond; or
- Vehicle (e.g. a truck, car or van).

Figure 31: Personnel and path target appearance in two colour fusion approaches from Toet and Franken, 2003.

A number of military investigators have investigated the performance of fusion systems for classical target detection, recognition and identification. Given the sensitive nature of the results, these reports are not available in the open literature. One of the authors (Angel & Massel, 2005) investigated the performance of two optically fused Enhanced Night Vision Goggles (ENVGs) in a naturalistic setting. Target detection, recognition and identification performance was evaluated using friendly and enemy targets. Differences in fusion performance were observed between the two systems.

A number of other investigators have evaluated simple target detection performance of fusion systems in laboratory environments - see Essock, McCarley, Krebs & DeFord (1999) and Rockinger & Fechner (1998). Images were presented to observers and the time to detect and the accuracy of detection was recorded. Images with and without targets were sequentially presented to an observer using a computer display in a controlled environment. The number of images presented to an observer varied according to the test but sessions were typically restricted to 30 minutes due to fatigue concerns. Experiments investigating detection, recognition or detail assessments typically began with subject training and a number of practice trials. During familiarization training subjects are first shown how targets actually appear the different fusion approaches – see Figure 32.

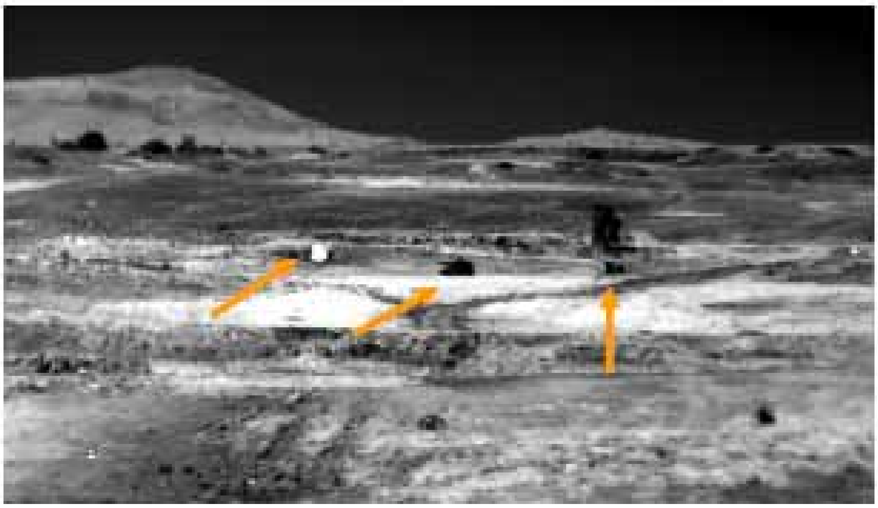

Figure 32: Sample image identifying detection targets from Lanir (2005)

The simple detection test protocol followed a typical signal detection procedure. The stimuli (images) were presented onto a computer screen in a dimly lit room. Random noise was first presented to the subject for brief period of time (Toet & Franken, (2003) utilized 400m), followed by the presentation of the image stimulus for another brief period of time (500ms). The sizes of the objects in the stimulus image were controlled. Subjects were required to indicate as rapidly as possible the presence or absence of the different target classes. The brief target exposure and target size served to prevent scanning eye movements and to force observers to make a decision based solely on the stimulus presented. Toet and Franken (2003) state that scanning behaviour may differ among image modalities and target types. An energy mask then followed which helped to erase any possible after images and equalled between subjects processing time. The noise image was controlled for image size (same as the target) and colour. The accuracy results were evaluated using the signal detection theory discriminability index -d´. The discriminability index uses hit and miss rates and a Receiver Operating Characteristic (ROC) curve – see Figure 33.

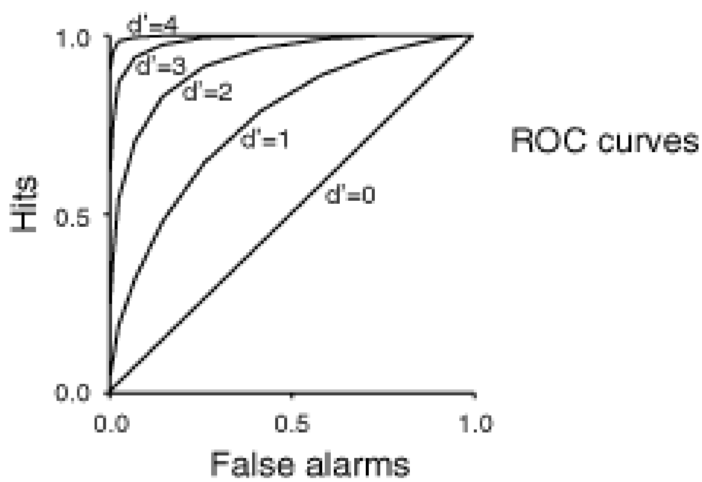

Figure 33: Sample ROC curve from Heeger (2007)

4.3.2.1.2 Situational Awareness Assessment

Situation Awareness (SA), as defined by Endsley (1995 pg 36) "is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status". Endsley (1995) describes SA as having three levels or phases:

- Level 1 is the perception of elements in the environment;
- Level 2 is the comprehension of the current situation; and
- Level 3 is the projection of future status.

Level 2 SA not only includes the perception of elements found in Level 1 SA, but also the understanding of the significance of the elements in light of the operator's goal. According to Endsley, (1995 pg 37)– in Level 2 SA, the operator forms a holistic picture of the environment.

Toet and Franken (2003) assessed situational awareness by asking subjects to report the relative location of personnel relative to a fixed landmark. Three sets of SA evaluation images were developed and based upon operational scenarios developed for the Royal Netherland Army. The scenarios included the following:

- Guarding a UN camp;
- Guarding a temporary base; and
- Surveillance of a large area.

For the Guarding a UN camp Toet and Franken (2003) asked subjects to identify the position of the human target relative to a fence line: See Figure 34. Targets were located on the left, center and right of the fence apex. In the guarding the temporary base the test was to determine the location of the person relative to a tree line and finally the surveillance test include the determination of a target relative to a path. As with their detail detection exercise, images were gathered by Toet and Franken (2003) for laboratory based psychophysical testing.

Figure 34: Sample human target from UN camp SA assessment (Toet, 2002)

Angel and Vilhena (2005) investigated the performance of two optically fused Enhanced Night Vision Goggles (ENVGs) and dedicated thermal and image intensified camera systems for scout and sentry performance in a naturalistic setting. Fused systems were reported to have performed better than stand alone LWIR or Image Intensified systems.

4.3.2.1.3 Spatial Orientation

The effects of colour fusion on global situational awareness has been investigated by Krebs and Sinai (2002) and Toet and Franken (2003). These investigations centered on the evaluation of scene orientation, i.e. the perception of the global scene rather than local demands. The ability to accurately perceive horizons and water features is difficult with monochrome fusion images and individual sensors. Both investigations manipulated the presentation of scenes, i.e. either a scene was upright or inverted.

While Krebs and Sinai (2002) manipulated image orientation alone, Toet and Franken (2003) also assessed the observer's ability to perceive the horizon. Both investigations reported that Infra-Red (IR) sensors alone performed the poorest at the perception of whether the image was upright. Toet and Franken (2003) also reported that IR sensors also performed the poorest at detecting the location of the horizon – see columns one and two in Figure 35. Both investigations found that image intensified sensors performed the best for spatial orientation.

While fusion did not improve spatial orientation in Toet and Franken (2003), fusion did improve the detection of terrain features and targets in the global scene.

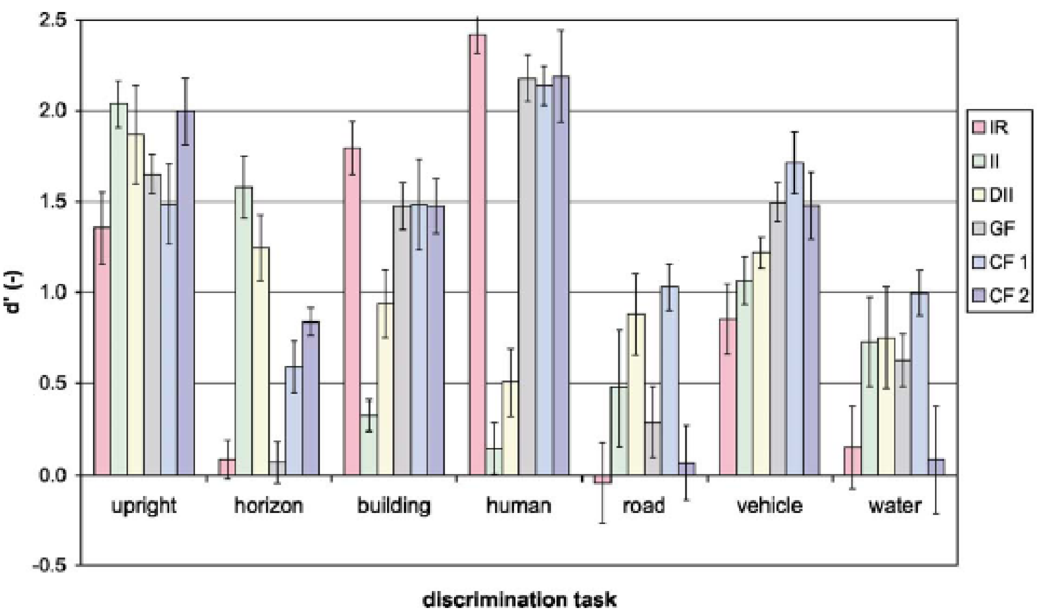

Figure 35: Situational awareness results from Toet and Franken (2003).

(Note: infrared (IR), single-band or gray scale (II) and double-band or colour (DII) intensified visual, gray scale fused (GF) and colour fused (CF1, CF2) imagery.)

4.3.2.2 Qualitative Subjective Fusion Assessment

A variety of scales and methods have been used to evaluate the quality of fusion images, typically a subject is asked to rank or rate the quality of the image on a linear or ordinal scale. Three approaches are discussed in the literature, simple ranking, Single Stimulus Continuous Quality Evaluation (SSCQE) and Double Stimulus Continuous Quality Evaluation (DSCQE).

Simple ranking involves the assessment of the fusion images by panel that individually ranks the images into their perceived order of image quality. While Chen and Blum (2000) utilized a "small evaluation group" to assess the fusion image quality, Petrović, (2007) used 100 subjects to evaluate nine distinct fusion approaches.

SSCQE, subjects are asked to asses the quality of a fusion image using a linear scale. Descriptive anchors (bad, poor, fair, good and excellent) have been used on a 1-100 continuous scale. The results of the image assessment are ranked to determine the relative quality of the images and thus the fusion approach performance. Other investigations have simply used vision or operational experts to simply rank the qualities of the fusion images).

SSCQE requires familiarization training for subjects to develop a quality frame of reference for the images they are about to assess. If evaluations require multiple sessions then scale realignment techniques are required (i.e. an image that rated 50 on session one should be similar in value on subsequent days). Sessions typically involve the sequential presentation of images to a reviewer who scores the quality on a scale.

DSCQE (or paired comparison) involves the comparative evaluation of pairs of fusion images (same image but different fusion approach) - see Figure 36. The approach utilizes the Law of Comparative Judgment, where the percentage of the time one fusion approach is preferred over another is used as an index of the relative quality of the fusion approaches. Pairwise comparisons forms the basis of Thurstone Scaling and the approach has been found to generate reliable data about the relative subjective quality of entities.

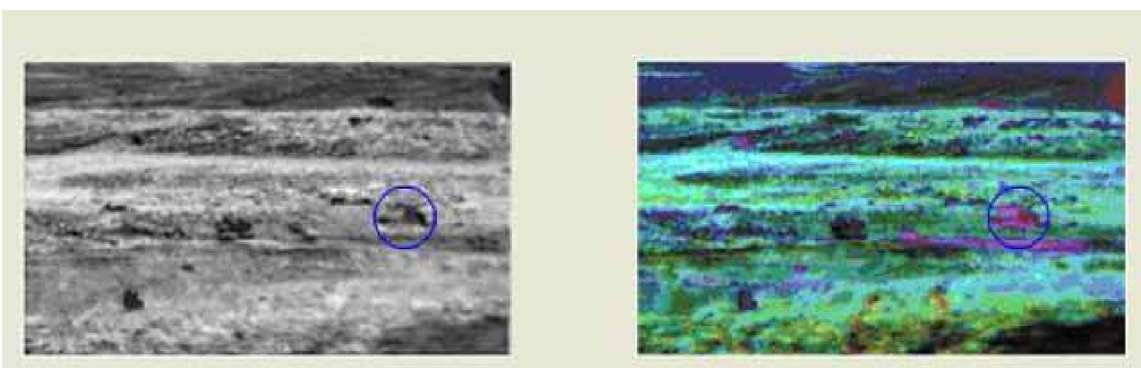

Figure 36: Paired comparison sample from Lanir (2005)

The Thurston method requires respondents to compare two options that must be evaluated. They are asked to choose only one selection (i.e., which fusion image is better?). Z-values are then determined based on a normal distribution based on the "winning percentage" of these comparisons. The results are then converted to a one-dimensional numbered scale using an arbitrary reference point. The key feature in Thurstone scaling is that in addition to being able to determine the ranking order of images, the distance and spread between respective options is determined. While the paired comparison method is an excellent technique for evaluating differences between fusion images, the number of comparisons can become excessive as more fusion approaches (n) are utilized.

In summary, ranking and Mean Opinion Score (MOS) techniques such as SSCQE and DSCQE have been used by researchers to evaluate fusion image quality. The approach allows subjective evaluation of the performance of different fusion algorithms. Subjective evaluation approaches have typically utilized still images in their examination of fusion performance; only two studies reviewed utilized video.

4.3.3 Objective Evaluation Approaches

Objective measures utilize input images and the fusion image to develop a numerical score of the success of the fusion process (Petrović, 2007). And unlike subjective assessments which have significant organizational and logistic requirements, objective measures can be computed automatically. While a number of researchers have developed their own software to evaluate fusion performance a number of evaluation tools have been collated into software modules.

4.3.3.1 Objective Evaluation Software

MATIFUS is a downloadable Matlab toolbox for image fusion. It is a collection of functions that supports image fusion operations and tools have been developed to evaluate objective fusion performance. Currently the toolbox supports multiresolution decomposition techniques (Wavelet, Steerable Pyramid, Quincunx Lifting Scheme, LAP and GRAD). The MATIFUS multiresolution interface allows the manipulation of the fusion algorithm parameters such as filters, bands, weighting coefficients etc – see Figure 37.

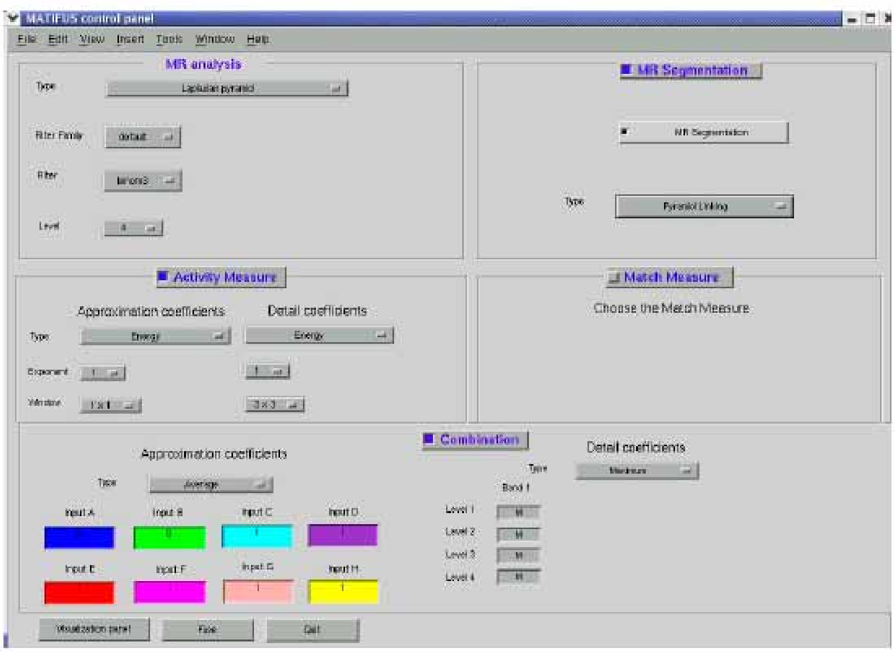

Figure 37: Control panel of MATIFUS

Canga (2003) developed a Matlab fusion toolkit as part of his final year project at the University of Bath. The toolkit includes a number of fusion techniques and evaluation metrics.

A third Matlab image fusion application is called the Image Fusion Toolbox by Metapix. The toolbox includes the following fusion methods: linear superposition, PCA weighted superposition, select minimum value, select maximum value, LAP, sd pyramid, ratio pyramid, GRAD, DWT using DBSS (2,2) wavelets, SiDWT using haar wavelet and MORPH. As with MATIFUS the functions are accessed through a graphical interface which allows image input, output and parameter manipulation – see Figure 38.

Figure 38: Control panel for the Image Fusion Toolbox

A second image fusion toolbox was developed by the Canadian Company - Airborne Underwater Geophysical Signals (AUG Signals) for use with Matlab and IDL. The toolbox contains traditional as well as unique AUG Signals fusion approaches. AUG Signals Electro-optical Remote Sensing Software is a complete software package incorporating a graphical user interface (see Figure 39), fusion algorithms, and advanced image processing methods (including image registration, detection, region classification, restoration, fusion, and hyperspectral data analysis.)

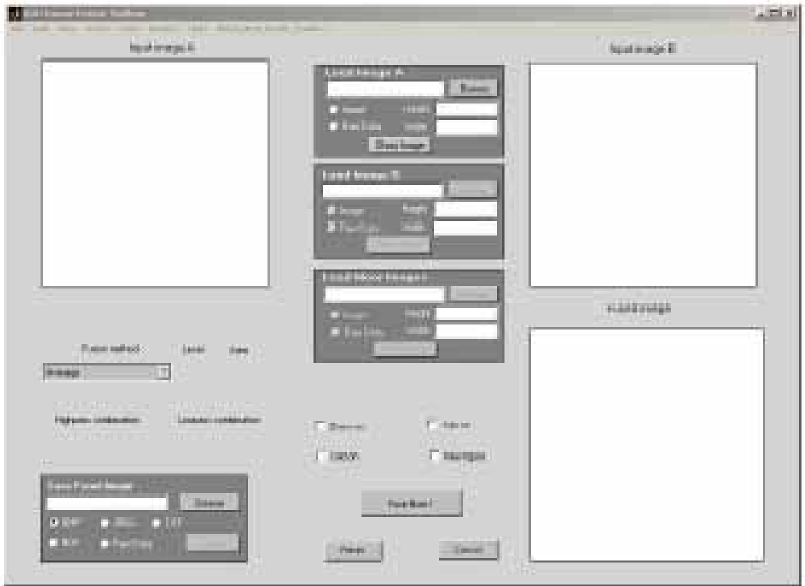

Figure 39: Control panel for AUG Signals Image Fusion Toolbox

Another open source compendium of tools for image fusion is the Generalised Image Fusion Toolkit (GIFT) from Mueller, Maeder, and O'Shea. (2006). GIFT currently implements quadrature mirror filter discrete wavelet transform (QMF DWT) multi-scale fusion algorithms. GIFT is built upon the Insight Toolkit (ITK) which is an open-source software system able to perform a range of registration and segmentation algorithms in two- or three-dimensions. Although GIFT currently only implements pixel-level multi-scale image fusion, efforts are underway to add image fusion metrics into the program. Possible metrics include the root mean square error (RMSE) between a “ground-truth” image and the fused image, the RMSE between the input images and the fused image, image entropy, mutual information, spatial frequency, edge strength and orientation, and the image quality index (IQI).

4.3.3.2 Objective Evaluation Metrics

A number of fusion evaluation approaches are based upon objective metrics developed for simple image quality assessments. Image quality metrics are used by manufacturers in the design and development of scanners, printers, digital cameras and displays. A number of objective methods have been developed to evaluate components of image quality, i.e. granularity and visually weighted mean square error is used to predict stochastic noise (Farrell, 1999). Distortion metrics have also been developed to predict visual performance with test targets and patterns. These metrics typically require an ideal or “ground truth” image in which to compare manipulation performance. To support this effort, the image engineering community has developed a large database of “ground truth” test images to assess compression performance.

Objective metrics have also been developed to assess fusion performance. Unlike traditional image quality metrics which use a “ground truth” image, ideal fusion images are not available. Adjusting fusion filter bands, decomposition levels, weighting parameters, window sizes, etc. will affect fusion performance.

A large number of objective measures have been proposed to evaluate fusion performance, these include Root Mean Square Error (RMSE), Image Quality (QW), Fusion Quality Measure (Q) to name a few. Xiaochun and Chin (2005) classified objective measure into four categories:

- Methods based on statistical characteristics;
- Methods based on definition;
- Methods based on information theory; and
- Methods based on important features.

Please see Chen and Blum (2000); Zheng et al. (2004); Xiaochun and Chen (2005); Wang, Shen, Zhang and qui Zhang (2003); Tian, Chen and Zhang (2004); Tsagaris and Anastassopoulos (2006); Zheng et al. (2005); Piella (2004) for other articles detailing objective evaluation metrics. Objective evaluation approaches will be described in greater detail in the following section.

4.3.3.2.1 Objective Evaluation Using Statistical Characteristics

A number of objective measures that utilize spectral information are available to assess fusion performance. Some of these measures such as Spatial Frequency (SF), Root mean Square Error (RMSE), Peak Signal to Noise ratio (PSNR), Image Quality Index (IQI) and entropy require the use of a ground truth image to derive their measure. As stated earlier this is not the case for most fusion applications; the ideal fusion image is not known. The following is a non-exhaustive list of statistical objective measures which use spectral information to evaluate fusion performance. Please note that only approaches which do not require the use of “ideal” images are included. :

Standard Deviation: Differences between the average gray value (reflects average intensity to vision) of the fused image are compared to the fusion image. It is believed that higher standard deviations correlate with better vision. Additionally better vision correlates to an average gray value of 128.

Contorted value of spectral image: This measure reflects the spectral distortion of the fusion image. This is computed by determining the absolute difference between the fusion image and the original images. Better fusion results in a lower contorted value of image spectral.

Spectral correlation: This measure is utilized in wavelet decomposition methods, where correlations in the horizontal, vertical and diagonal directions are determined between the fusion image and the source images. Better fusion is believed to correspond to higher spectral correlations.

Standard gray scale difference: This measure corresponds to the contrast of the fusion image. The distribution of the gray values across the image is compared to the mean gray value. The measure predicts the enhancement of contrast.

Fechner-Weber contrast measure: Fechner’s law states that the sensation increases with the logarithm of the stimulus. The human retina corrects all sensor values using a local comparison with the mean response from the receptor neighbours (Rojas, 2007)

Target Interference Ratio (TIR)/Target-Background Interference Ratio (TBIR): This measure is based on the assumption that if a target contrasts highly with its background, it will be easier to find. While TIR and TBIR indicate the separability of a target from its background, the TBIR favours uniform targets against uniform backgrounds while the TIR does not (Peters & Strickland, 1990).

Fisher Distance: Discriminant function analysis is used to determine which variables discriminate between two or more naturally occurring groups. The Fisher Linear Discriminant maps many dimensions, i.e. source and fusion images on to one. The resulting quadratic equation or Fisher distance (Fisher's vector) provides a linear estimate of differences. The optimum fusion process should possess the highest Patrick-Fisher contrast distance.

Fractal dimensions: Fractal dimensions can describe the abundance degree of texture characteristics and the variety of pixel values

Image Noise Index (INI) is used as an index to create a clear picture of the improvement or deterioration of the fused image. If INI is positive there is an improvement in the quality of the fused picture. INI is related to the signal-noise ratio and utilizes the image entropy of the original, fused and restored image.

Signal Noise ration (SNR) Estimation (QS): This metric estimates the noise and blurring in images.

Mannos-Sakrison's Filter Metric: This metric is used to compare the fusion image with the source images in the frequency domain. The model is sensitive to middle range frequencies. (Chari et al. 2005)

4.3.3.2.2 Objective Evaluation Based on Definition

In addition to statistical classification methods, Xiaochun and Chen (2005) classify objective metrics according the geometric detail of the fusion image. Xiaochun and Chen identify three definition parameters, average grads, spatial frequency and wavelet energies.

Average grads: This approach compares how well the locations within images compare to each other. The measure is used to evaluate the image's degree of clarity. Increased sensitivity to small details is reflected in higher gradient scores. The gradient reflects the contrast differences between images, especially at edges where image gradients are strongest.

Spatial frequency (SF): Spatial frequency is used to measure the overall activity level of an image.

Wavelet Energies: This metric is based upon wavelet energy after image decomposition.

4.3.3.2.3 Objective Evaluation Based on Information Theory

Fusion performance can be assessed using information theory, in that fusion images should contain more information than their source images. Information entropy can measure the extent of image spectral information. Entropy is determined by evaluating the information content of an image. Entropy is sensitive to noise and other unwanted fluctuations.

Correlation information entropy: This is a constructed parameter which assesses information overlap between source and fused images.

Cross Entropy: Cross entropy denotes the correlation extent of information between images. The better the fusion process the higher the correlation and cross entropy.

Union Entropy: Union entropy is the measurement of information correlation and union information amongst multi-images.

Image Entropy: This represents the amount of information that is transferred from the source images to the final fusion image. Image entropy does not take into account the overlap of information from the source images. While the image entropy metric makes it difficult to compare different data sets, it is used to assess fusion approaches which operate globally (averaging or PCA) as well as methods which focus on detailed content (DWT and morphological fusion approaches).

Image Fusion Performance Measure (IFPM): this measure utilizes the mutual information as well as conditional information to evaluate the amount of information transferred from the source images to the final fusion image. This measure utilizes common information only once in its calculation.

Information Based Measure (MI): Mutual information represents the amount of information that is transferred from the source images to the final fusion image.

4.3.3.2.4 Objective Evaluation Based on Important Features

There are two general categories of important features found in fused images, edges and regions of interest.

Evaluation method based on protected factor of edge information

Petrovic and Xideas (2005) developed a metric (QE) which evaluates the amount of edge information that is transferred from source images to the fused image. A Sobel detector is used to detect edges, field strengths and orientations. This metric evaluates the loss of edge information between the fusion image and the source image. This measure is based upon the theory that the human visual system resolves uncertainty by extracting information contained in illuminated variations or edges rather than actual signal values. The measure thus uses only edge information and not regional information.

Edge Dependent Fusion Quality Index (QE): The edge-dependent fusion quality index uses both images and edges to determine its value. In this measure edges get higher weight.

Evaluation method based on image quality

Fusion Quality Measure/Index (Q): The fusion quality measure reflects how much salient information contained in each of the input images has been transferred into the composite image. In this measure all areas of the image are treated equally but this is contrary to human vision where some regions have higher importance, i.e. a tree-line bordering on an open field.

Weighted Fusion Quality Index (QW): The weighted fusion quality index reflects how much salient information contained in each of the input images has been transferred into the composite image. In this measure areas which are perceptually important get higher weight.

Universal Image Quality Index (UIQI); this quality metric is based upon the Wang and Bovik (2002) Structural Similarity (SSIM) measure. The UIQI gives an indication (Qb) of how much of the salient information contained in the source images is transferred to the fusion image. (Cvejic, Loza, Bull and Canagarajah, 2005)

Visual Difference (VDA): This measure evaluates fusion performance as the total area affected by visible differences in the fused image as compared to source images.

5 Discussion

5.1 Hardware – Sensors

The latest image sensor market is strongly driven by the camera cell phone and digital still camera applications and is moving toward the larger number of pixels and the smaller pixel size (Mizobuci, Adachi, Yamashita, Okamura, Oshikubo, Akahane, and Sugawa, 2007). This drive has resulted in significantly smaller image sensors. More specific to military applications, there has been a recent push for NVG sensor improvements that has been driven by operational requirements formed by military NVG users. The top desired enhancements for NVGs are listed below (Estrera et al. 2003):

- Multispectral image fusion;
- Lighter weight;
- Smaller ;
- Reduced power consumption;
- Higher resolution;
- Increased range;
- Facilitate individual movement techniques;
- Colour image; and
- Image reliability.

This list highlights some deficiencies with the current NVG technologies. In terms of a helmet based sensor fusion system, the first three enhancements need to be immediately addressed.

5.1.1 Sensor Criteria

There are a number of important specifications to consider in selecting sensors for image fusion. In this particular application to SIHS, specifications that need to be considered with the ideal requirements are:

Table 6: SIHS Sensor Specifications

Specification	Ideal
Size (length, width, height)	Small, small enough to mount on helmet, approx 2x3x2 inches
Weight	Lightweight, approx 2lbs or less
Resolution	Average to good, at least 640 x 480 pixels
Real-time image capture	Frame rate at least 30 Hz
Sensitivity	High sensitivity

To be considered real-time processing, the frame rate was set to be at least 30 frames per second (fps or Hz). The frame rate is usually dependent on the resolution. The higher the resolution, the lower frame rate; and the higher the frame rate the lower the resolution. It should be noted "Maximum Frame Rate" column in Annex A the maximum frame rate is reported, that is not necessarily correlated to the resolution. This correlation was taken into account in the analysis. To satisfy the specification a sensor would have to have at least a 640 x 480 resolution and at least 30 fps.

These characteristics will be considered in the evaluation of the sensors presented below. There are several other parameters to consider, that are not as important in this evaluation. They are listed below for reference for future consideration:

- Performance features (ex. Gain control, cooled, high speed, anti-blooming);
- Physical features;
- Lens mounting;
- Shutter control;
- Operating environment; and
- Battery life.

The anti-blooming or "halo free" is an ideal feature to have. It is a severe deficiency of I^2 sensors when they encounter bright light. It results in the loss of imaging information due to I^2 halo, especially at long distances (Estrera, Ostromek, Bacarella, Isvell, Iosue, Saldana, Beystrum, 2002). Figure 40 shows the difference between having the anti-blooming feature and not having it in an intensified image of people around a vehicle with bright light sources.

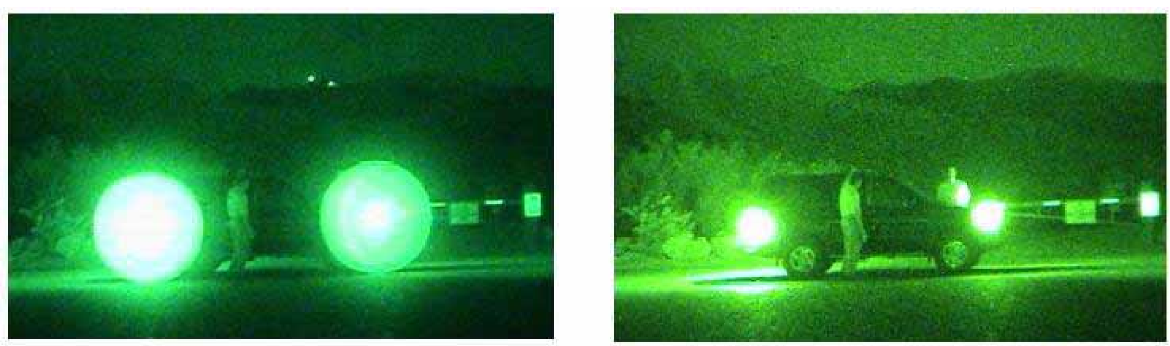

Figure 40: Comparison of anti-blooming or halo free feature (Estrera et al, 2003)

Image fusion of I^2 and IR sensors is of great importance. A comprehensive table, taken from Estrera et al. (2003) shows the positive and negative aspects of each individual sensor and the fusion result. Image fusion allows the positive aspects of each sensor to operate, while the negative aspects may not be present.

Table 7: Comparison of Positive and Negative Aspects of I^2 and IR Fused Sensors (Estrera et al. 2003)

Negatives		Positives		
I^2/IR	Characteristic	I^2/IR	Characteristic	Fusion Result
I^2	No Laser Designator Detection	IR	Excellent Laser Designator Detection	Good Laser Designator Detection
I^2	No Total Darkness	IR	Excellent Thermal in total darkness	Good Total Darkness vision
I^2	Poor Long Range Vehicle ID	IR	Excellent Long range Vehicle ID	Good Long Range Vehicle ID
I^2	No Thermal Contrast Detection	IR	Excellent Thermal Contrast Detection	Good Thermal Contrast Detection
IR	Poor Low Thermal contrast target Det.	I^2	Excellent Low Thermal Contrast Target Detection	Good Low thermal contrast detection
IR	No Artificial lights detection	I^2	Excellent Artificial Light detection	Good Artificial Light detection
IR	No Shadow Detection	I^2	Excellent Shadow Detection	Good Shadow Detection
IR	No Silica Glass Penetration	I^2	Excellent Silica Glass Penetration	Good Silica Glasss Penetration

NOTE: I^2 (Image Intensifier), IR(Infrared) defined as NIR, SWIR, MWIR, LWIR

5.1.2 Sensor Evaluation

A binary evaluation was done on each type of sensor to establish whether or not it met the specification criteria. A summary of the evaluations is presented in the subsequent tables. If the sensor met the specification, it is indicated by a "✓" and if did not it is indicated by a "✘". Items that do not have an"✓" or "✘" indicate there was missing information for that specification.

Table 8: LLLTV Evaluation

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
DVC	DVC-1412 Series -- DVC-1412AM-MS	✓	✓	✓	✘	✓	4
DVC	DVC-1412 Series -- DVC-1412AM-MT	✓	✓	✓	✘	✓	4
DVC	DVC-1412 Series -- DVC-1412AC-00	✓	✓	✓	✘	✓	4
DVC	DVC-1412 Series -- DVC-1412AC-TE	✓	✓	✓	✘	✓	4

Table 8: LLLTV Evaluation (continued)

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
Intevac	E2006 Low Light Level Camera	✓	✓	✓	✓	✓	5
NAC Image Technology	HSV High-Speed Color Video System - HSV-500C3	✓	✓	✗	✓	✗	3
NAC Image Technology	Memrecam fx -RX5 Micro Camera Head	✓	✓	✓	✓	✗	4
PCO Imaging	PCO Series- Model PCO.1600	✗	✗	✓	✓		2
PCO Imaging	PCO Series -Model PCO.2000	✗	✗	✓	✗		2
PCO Imaging	PCO Series - Model PCO.4000	✗	✗	✓	✗		2
PCO Imaging	Pixelfly Series - Model Pixelfly	✓	✓	✓	✓		4
PCO Imaging	Pixelfly Series - Model Pixelfly QE	✓	✓	✓	✗		3
PCO Imaging	Sensicam Series - Model Sensicam EM	✓	✗	✓	✗		2
PCO Imaging	Sensicam Series - Model Sensicam QE	✓	✗	✓	✗		2
PCO Imaging	Sensicam Series - Model Sensicam QE Double Shutter	✓	✗	✓	✗		2

Intevac's E2005 LLL camera met the specifications for the SIHS application. PCO Imaging Pixelfly met all the specifications, however, information was missing regarding the sensitivity.

Table 9: CMOS Evaluation

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
Intevac	NightVista E2010	✓	✓	✓	✓	✓	4
Intevac	NightVista E3010	✓		✓	✓		3
Irvine Sensors Corp.	MVC-FF0229	✓		✗	✓		2
PCO Imaging	PCO Series -- Model PCO.1200 HS	✗		✓	✓		2
PCO Imaging	PCO Series -- Model PCO.1200 S	✗		✓	✓		2
Prosilica Inc.	GE640C -- 02-2001A	✓		✗	✓		2
Vision Research Inc	High Speed Camera -- Phantom® v6.2	✓		✗	✓	✗	2

Unfortunately, most of the CMOS sensors were missing information regarding weight and light sensitivity. From the above analysis, Intevac's E2010 is the most suitable camera for the SIHS application because it met all of the specifications.

Table 10: SWIR Evaluation

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
FLIR	SC4000 HS-NIR/ SC6000 HS-NIR			✓	✓		2
Intevac	LIVAR 400 Short Wave Infrared Camera	✓		✓	✓		3
Sensors Unlimited Inc (Goodrich)	SU640SDV-1.7 RT SU640SDV Vis-1.7 RT High Resolution InGaAs and Vis-InGaAs SWIR Area Cameras	✗	✗	✓	✓		2
Sensors Unlimited Inc (Goodrich)	SU640SDWH-1.7 RT SU640SDWHVIS-1.7 RT High Resolution Windowing InGaAs and Vis-InGaAs SWIR Area Cameras	✗	✗	✓	✓		2
Sensors Unlimited Inc (Goodrich)	SU320KTX-1.7RT High Sensitivity InGaAs SWIR Camera	✓	✗	✗	✓		2
Sensors Unlimited Inc (Goodrich)	SU320M-1.7RT InGaAs SWIR Camera	✓	✓	✗	✓		3
Sensors Unlimited Inc (Goodrich)	SU320MX-1.7RT High Sensitivity InGaAs NIR MiniCamera	✓	✓	✗	✓		3
Sensors Unlimited Inc (Goodrich)	SU320MVis-1.7RT Visible and SWIR Response InGaAs NIR MiniCamera	✓	✓	✗	✓		3
Sensors Unlimited Inc (Goodrich)	SU320MSVis-1.7RT Visible and SWIR Response InGaAs MiniCamera	✓	✓	✗	✓		3
Lumitron	NIR320 OEM InGaAs Near-Infrared Camera	✗	✗	✗	✓		1

There was no information provided for the thermal sensitivity of the SWIR sensors. The evaluation above shows that Sensors Unlimited has four cameras: SU320M-1.7RT InGaAs SWIR Camera, NIR MiniCamera, and SU320MVis-1.7RT Visible and SWIR models met most (3 out of 5) specifications for the SIHS application. However, these sensors did not quite meet the resolution specification as they only had a 320 x 240 resolution where the minimum desired is 640 x 480. The other Sensors Unlimited cameras met the resolution and real time requirements, however were slightly big (6"x3"x3"). Intevac's LIVAR 400 Short Wave Infrared Camera would be the most suitable for SIHS (for resolution and real time), as it also met three specifications but was missing information for the weight.

Table 11: MWIR and LWIR Evaluation

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
DRS NVEC	UTWS (Urban Thermal Weapon Sight II)	✗	✓	✗	✓	✓	3
DRS NVEC	CSTWS (Crew Served Thermal Weapon Sight II)	✗	✗	✓	✓	✓	3
DRS NVEC	MX-2 (Rugged miniature thermal imager)	✗	✗	✗	✓	✗	1
DRS NVEC	COBRA-IR (Covert Over Barrier Recon Assistant - Infrared)	✗	✓	✗	✓	✗	2
DRS NVEC	HelmetIR	✓	✓	✗	✗	✗	2
DRS NVEC	Mini-IR Plus (hand-held thermal imager)	✗		✗	✓	✗	1
DRS NVEC	PVS-7 Style (Single tube NVG)	✗					0
DRS NVEC	MANTIS (Multi-Adaptable Night Tactical Imaging System)	✓					1
DRS NVEC	4x Raptor (4-power night vision weapon sight)	✗	✓				1
DRS NVEC	6x Raptor (6-power night vision weapon sight)	✗	✗				0
ELCAN (Raytheon)	SpecterIR+			✗			0
FLIR	ThermoVision Photon	✓	✓	✗			2
FLIR	ThermoVision ThermoSight		✓				1
FLIR	ThermoVision A10	✓		✗			1
FLIR	SC4000 HS MWIR/ SC6000 HS-MWIR			✓	✓	✓	3
FLIR	SC4000 HS LWIR/ SC6000 HS-LWIR			✓	✓	✓	3
Irvine Sensors	Personal Miniature Thermal Viewer	✓	✓	✗	✓	✓	4
Irvine Sensors	CAM-NOIR Thermal Camera			✗			0
Irvine Sensors	Miniature Camera			✓			1
L3 Communications Thermal-Eye	X200xp	✗	✓	✗	✓	✓	3
L3 Communications Thermal-Eye	3600AS	✓	✗	✗	✓	✓	3
L3 Communications Thermal-Eye	3620AS	✓	✗	✗	✓	✓	3
L3 Communications Thermal-Eye	3640AS	✓	✗	✗	✓	✓	3
Lumitron	UC320U OEM Microbolometer Infrared Camera	✓	✓	✗	✓	✗	3
Lumitron	UC320D OEM Microbolometer Infrared Camera	✗	✓	✗	✓	✗	2

Many of the sensors were missing information regarding thermal sensitivity. From the above analysis, Irvine's Personal Miniature Thermal Viewer met 4 out of 5 of the desired specifications. However, it did not quite meet the resolution specification as it is only 320 x 240. Other suitable candidates considering the 30 fps and 640 x 480 resolution was FLIR cameras SC4000 HS MWIR/ SC6000 HS-MWIR and LWIR. The FLIR cameras data sheets did not provide any information on size or weight, otherwise it satisfied all other specifications.

Table 12: EBAPS Evaluation

Manufacturer	Sensor	Size	Weight	Resolution	Real Time	Sensitivity	TOTAL "✓"
Intevac	NightVista			✓	✓		2
Intevac	ISIE6			✓	✓		2
Intevac	ISIE10			✓	✓		2

There was a great deal of missing information on the data sheets provided by Intevac for the EBAPS. Model ISIE10 is still in its development stages. As size, weight, and sensitivity are unknown, it cannot be determined whether any of these sensors is suitable for SIHS. However, the frame rates did not meet the desired specification for NightVista, ISIE6, and ISIE10, as they were only 30, 27.5, and 37 respectively.

All sensor technical datasheets recommended for SIHS are in Annex C, except for EBAPS as there were none available.

5.2 Hardware – Fusion Boards

An important capability for fielded image fusion systems is computational co-registration. Dynamic scenes typically have foreground/background objects in relative motion, there is no single computational mapping for visible/thermal infrared cameras with any degree of parallax that will bring both image inputs into exact alignment at all times (Wolff et al. 2006). The new Equinox DVP-4000 allows for co-registration while previous models did not and does not require as much power as the previous Equinox models. The Imagize FP-3500 uses a closed source algorithm approach while the Equinox DVP-4000 uses an open source approach with algorithms developed by Waterfall Solutions (Surrey, England). However, for an open source desk top application for image fusion the Octec ADEPT60 is widely used and features multiple algorithm capability with multiple analog and digital inputs. Due to the lack of literature and specifications present on the image fusion processors a full criterion based evaluation cannot be performed on the available processors.

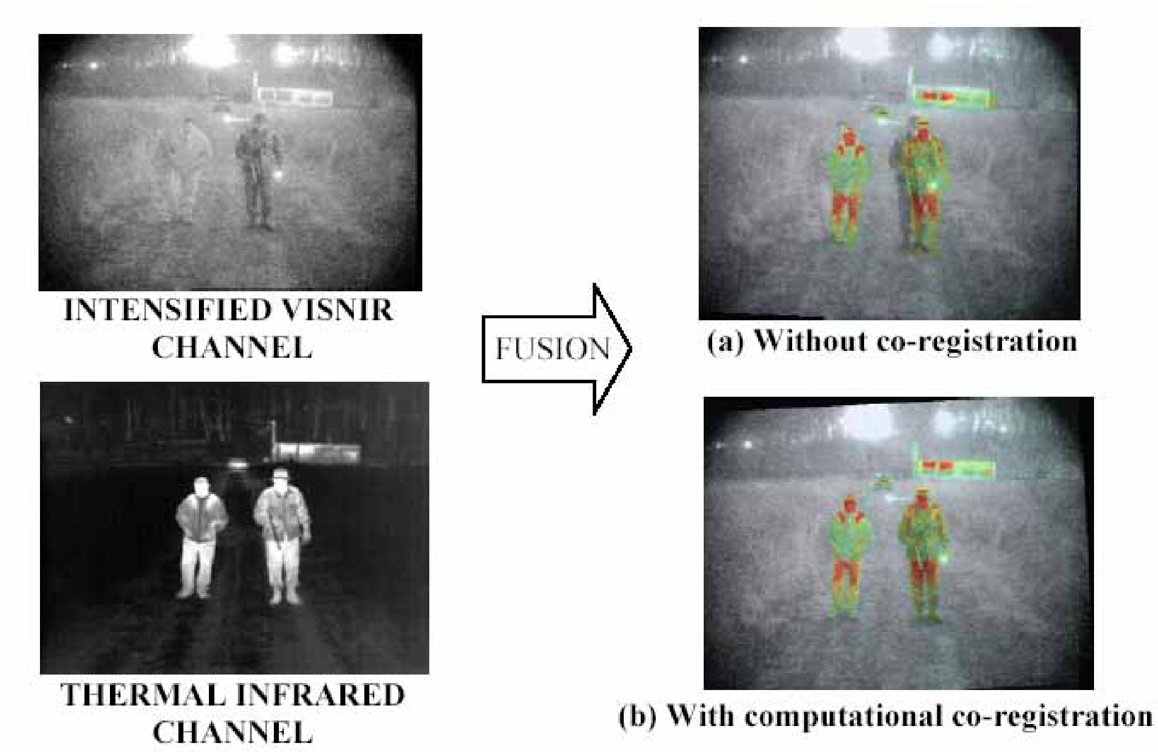

Figure 41: Example of co-registration (Wolff et al, 2006)

5.3 Fusion Algorithms

All the previously discussed algorithms have advantages and disadvantages. A description of the specific advantages and disadvantages of each algorithm is available in Table 13. According to several studies, the SiDWT generally outperforms all other algorithms in both subjective and objective measures. The simple averaging technique, albeit easy to use it, all large contrast values will be suppressed in the resulting fused image. Using the PCA the fused image tends to be of lesser quality than the input images due to the common selection of only the 1st Eigen value for the fused image. The GRAD and RoLP have decreased image sharpness and creates spots on the fused image. A simple DWT algorithm produces favourable subjective and objective results but produces an image that is not shift-invariant. Even though it may have increased computational and time demands the SiDWT, or variations of it, is the algorithm that may produce the best fusion results for night time imagery. The LAP also produces very good results for image fusion using night time imagery but it has the potential of changing the exact location of objects in the fused image when compared to the input images. Nonetheless, the LAP is the highest performing pyramid based fusion algorithm. However, depending on the type of objective tests and the type of input imagery the most desirable algorithm may change but the common conclusion from the literature is the SiDWT and LAP tend to outperform the other methods.

Table 13: Advantages and Disadvantages of Specific Algorithms

Algorithm	Advantages	Disadvantages
Pixel-Level		
Simple Averaging	- low computational demand - decreased time - simple - used as benchmark for comparison of other fusion methods	- high contrast pixel values in input image are depressed in value in the fused image
PCA	- selects optimal weighting coefficients based on information content - removes redundancy present in input image - compresses large amounts of inputs without much loss of information	- usually selects 1st Eigen value which does not contain all of the patterns between inputs - fused image will be of lesser quality than any of the input images - strong correlation between the input images and fused image is needed
Pyramid Based		
LAP	- most frequently studied pyramid transform - produces favourable results: both subjective and objective - able to pre-determine which pixels are used in the fused image	- decomposes images by a factor of 2, which restricts the composition of the fused image - does not distinguish between material edges and temperature edges, which may create an abundance of information and clutter the scene in the fused image - may alter exact location of objects in the fused image
MORPH	- removes image details without adding any gray scale bias or altering location - can extract objects of a certain size from an image	- decomposes images by a factor of 2, which restricts the composition of the fused image - performs worse than the LAP in subjective tests
GRAD	- produces horizontal, vertical, and diagonal pyramid sets compared to just horizontal and vertical - improved temporal stability over the LAP - transfers a greater amount of salient information when compared to the MORPH	- decrease in visual clarity when identifying targets - decrease in sharpness when compared to LAP - does not transfer as salient information as the LAP
RoLP	- encodes absolute luminance contrasts compared to absolute luminance differences in the LAP	- Performs inferior to LAP, GRAD, MORPH in objective performance measures - Decreased image sharpness when compared to LAP and GRAD - Produces algorithm-created spots in fused image

Table 14: Advantages and Disadvantages of Specific Algorithms (continued)

Wavelet Transforms	Refer to Section 4.2.4 for a list of the advantages of wavelet based methods over pyramid based methods	
DWT	- different rules are applied to the low and high frequency portions of the signal - Performs favourably when compared to other fusion methods	- is not shift-invariant - pixel by pixel analysis is not possible - not possible to fuse images of different sizes
SiDWT	- is shift invariant - improved temporal stability over DWT - redundancy of information allowing better detection of dominant feature - can be applied to any sized images for fusion - generally outperforms all other methods in subjective and objective tests - improved sharpness over most pyramid based methods	- requires increased computational and time demands
Feature-Level		
Edge Detection	- extract features dependant on changes occurring over a number of pixels rather than a single pixel - non-linear methods are able to preserve large-scale edges while removing structures smaller than a specified window	- difficult to select appropriate size threshold value for all applications - difficult to select appropriate window size for all applications - classical methods detect edges at only a single resolution - linear models are likely to blur important image features at each decomposition level

5.4 Metric Discussion

A large number of objective metrics and a smaller number of subjective metrics have been developed and utilized by researchers to assess fusion performance. The ability of the objective measures to predict human performance is a known concern of these researchers. Xiaochun and Chen (2005) noted that the use of objective measures is practical and effective only if the results are in accordance with subjective evaluation results. Farrell (1999, pg 286) stated that "there is no single image quality metric can predict our subjective judgements of image quality because image quality judgements are influenced by a multitude of different types of visible signals, each weighted differently depending on the context under which a judgement is made."

A review of the literature indicates that many of the earlier "statistical characteristic" objective measures failed in the rigor demanded in many scientific circles. Concerns with early objective measures include the following:

- Objective measures were based on static assessment of fusion and source images. Real time objective measures were not identified.
- The objective measures cannot be applied across all fusion approaches.
- The objective measures have not been adequately validated with human performance.
- If tested, the objective measures do not correlate well with human performance.
- The objective measures are task and condition dependent.

- Objective measures were developed with static images and are not currently designed for real-time application.

Measurement is the process observing and recording the observations that are collected as part of a research effort. For image fusion, researchers have suggested a variety of objective measures to assess the success of the fusion. Ideally the researcher has developed a theory upon which to base the validity of their measure (theoretical constructs). Construct validity is the assessment of how well the researcher translated their theories into actual measures. The limited review of the literature did not identify theoretical constructs for many of the older statistical objective measures. Given the limitations of simple metrics, researchers have focussed on developing metrics based on information theory and human perception (important features). Petrovic and Xydeas (2005) developed a metric based on the theory that “the human visual system (HVS) resolves uncertainty of visual stimuli by extracting information contained in illumination. Variations, that is, in changes (edges) rather than in actual signals” (Petrovic & Xydeas, 2005 pg 2). The authors reported a high correlation between subjective ratings and objective metrics which consider the preservation of input information in the form of edge parameters (strength and orientation) and the evaluation of edge’s perceptual importance. Convergent support for the validity of edge dependent measures was reported by Chen and Blum (2005). In their study Chen and Blum evaluated 28 night vision images using 13 different fusion approaches. Fusion performance was assessed using a limited expert subjective panel and seven objective measures. Chen and Blum reported that the Objective Edge Based Measure (QE) provides the best correlation between subjective and objective results.

The scientific method requires that metrics must have internal and external validity. Internal validity relates to the issue where a fusion approach did make a difference in operator performance. External validity relates to generalizability, “to what populations, settings, and treatment variables can this effect be generalized (Campbell and Stanley, 1963 pg 5.) Valid fusion performance measures should have face validity, predictive validity, and construct validity. The SIHS-TD fusion assessment program should focus on measures which are valid and meaningful.

Concerns with real time objective performance assessment could be overcome by a variety of means. Videos could be sampled at a known rate and each sample set of fusion and source images could be evaluated after data capture. The objective performance would then be determined by an average rating over the data set. If the fusion test bed is fast enough then it may be possible to conduct objective evaluations in real time or near real time with a minimum of lag.

A review of the subjective assessment literature examined in this study did not reveal any formal clinical assessments of fusion target recognition or identification performance using classical definitions (Holst, 2000). Because the classical definitions in themselves do not adequately address human or other urban targets adequately, the Night Visions and Electronic Sensors Directorate (NVESD) has recommended new definitions to adequately discriminate between friends from foe (Self & Miller, 2005). The draft definitions are as follows:

- **Detection**. The determination that an object or location in the field of view may be of military interest such that the military observer takes an action to look closer: alters search in progress, changes magnification, selects a different sensor, or cues a different sensor.
- **Classification.** The object is distinguished or discriminated by class, like wheeled or tracked, human or other animal. Possibilities are
- **Recognition**.
    - For vehicles and weapons platforms, the object can be distinguished by category within a class, such as tank or personnel carrier in the class of tracked vehicles.

    - For humans, the perception of individual elements, a combination, or a lack of, equipment, hand-held objects, and/or posture that can be distinguished to the extent that the human is determined to be of special military interest.
- **Identification**.
    - For military vehicles and weapons systems, the object is distinguished by model, such as M1A2 or T80.
    - For commercial vehicles, the object is distinguished by typically known model types.
    - For humans, the perception of individual elements or a combination of elements, such as clothing, equipment, hand-held objects, posture, and/or gender that can be distinguished to the extent that the human is determined to be armed or potentially combatant.
- **Feature identification.**
    - Commercial vehicles can be distinguished by make and model.
    - Individual elements of clothing, equipment, hand-held objects, and/or gender can be discriminated by name or country/region of origin

Future SIHS fusion studies should utilize the revised frame work as a basis for developing tasks and subjective performance measures, i.e. properly identifying an enemy target based on hand held objects.

Research is currently underway to develop adaptive fusion algorithms which adjust their parameters to optimize fusion performance (Piella, 2004). This approach requires objective measures which can be easily computed and automated. While adaptive fusion algorithms may not be available for utilization by SIHS, the approach should be available for future modernization programs.

Lead investigators in the image fusion community have indicated that they are now or soon will be, investigating task-specific fusion performance and the characterization of video fusion performance. The timing of the proposed fusion study by SIHS is thus occurring at an opportune time.

6 Conclusion and Recommendations

The literature search was conducted to support SIHS TD Vision SST in the development of their fusion test bed. The goal of the proposed test bed would be to help facilitate the evaluation of multispectral image fusion with potentially helmet portable sensors. The specific role of the fusion test bed would be to gather registered image data (source and fusion) for post hoc subjective and objective evaluations. Specific recommendations of sensors to acquire, fusion boards to investigate, fusion algorithms to employ and evaluation metrics are detailed below. Additionally suggestions as to what should be included in the test bed are described.

6.1 Sensor Hardware

Image fusion combines information contained in multispectral imagery and ultimately enhances situational awareness. The developments in sensor hardware have made sensor fusion a reality for defence applications. Varieties of sensor types were reviewed and are recommended for inclusion in the fusion test bed. The hope to positively confirm that small, relatively light weight, 640x480 resolution sensors operating at a minimum of 30Hz with high sensitivity are available was not realized. Sensors and cameras were identified that meet the resolution and real-time performance demands. The literature review identified that fusion studies utilized the following sensors

- Day camera;
- Night camera – either a LLLTV, ICMOS sensor or EBAPS sensor;
- NIR/SWIR sensor;
- MWIR (note MWIR was not utilized in man portable systems); and
- LWIR sensor.

Day Camera

There are large numbers of high resolution day cameras available on the market today and thus were not a focus of this search.

Night Camera

A large number of capable LLLTV (ICCD technology) – CCDs tend to be used in camera (sensors) that focus on high quality images with many pixels. CCD sensor light sensitivity is typically greater than that of CMOS. CMOS sensors usually have lower image quality and resolution. LLLTVs tend to be more cost effective than Infrared cameras. From the systems reviewed, Intevac's E2006 camera would be the most suitable for SIHS. It has a 1280 x 1024 resolution, 30 fps, and is only 2"x 2"x 3". The E2006 camera functions include non-uniformity correction, histogram equalization and horizontal image orientation. The Pixelfly by PCO Imaging could also be a suitable candidate for SIHS. It has a smaller resolution at 640 x 480 with a higher fps at 50Hz and is only 1.54"x 1.54"x 2.68".

ICMOS - ICMOS cameras are less expensive and they generally use less power than the CCD technology. It has a superior battery life over the CCD sensors. There are currently not many CMOS sensors that would meet the specifications for SIHS. Many of these cameras are used in manufacturing applications and commercial digital cameras. From the seven ICMOS sensors identified, Intevac's E2010 would be suitable for SIHS. The E2010 was designed for night surveillance applications. Similarly to the E2006, it has a 1280 x 1024 resolution, 30 fps, and is only 2"x 2"x 3".

EBAPS – Intevac has developed the proprietary EBAPS sensor. They were developed for commercial security camera applications. The NightVisa incorporates non-uniformity correction, bad pixel replacement, and histogram equalization image processing functions. As the ISIE10 is under development the Intevac models NightVista and IEIE6 seem like suitable candidates for SIHS. More information would be helpful, such as mechanical, size, and electrical specifications before pursuing the incorporation of these sensors into SIHS. The frame rate of all EBAPS did meet the desired specification, ranging from 27.5 to 37 Hz.

SWIR Camera

NIR/SWIR – There were no SWIR sensors the completely satisfied all the SIHS requirements. From the 10 SWIR sensors identified, Sensors Unlimited cameras were the most suitable for SIHS. They offer four miniature cameras: SU320M-1.7RT InGaAs SWIR Camera, NIR MiniCamera, and SU320MVis-1.7RT Visible and SWIR. However, these sensors did not quite meet the resolution specification as they only had a 320 x 240 resolution where the minimum desired was 640 x 480. The other Sensors Unlimited cameras met the resolution and real time requirements, however were slightly big in physical size at 6"x3"x3". Intevac's LIVAR 400 Short Wave Infrared Camera would be the most suitable for SIHS (for resolution and real time), as it also met three specifications but was missing information for the weight.

MWIR/LWIR Camera

MWIR and LWIR – There were also no MWIR and LWIR sensors that satisfied all the SIHS requirements. The most suitable sensor would be Irvine Sensors' Personal Miniature Thermal Viewer; however it did not meet the resolution requirement as its resolution was only 320 x 240. Irvine's camera uses a unique shutterless design, and there are custom optical, image processing packaging and interface options available. FLIRs sensor's SC4000 and SC6000 cameras appear to be suitable. The FLIR cameras data sheets did not provide any information on size or weights; otherwise they satisfied all other specifications.

6.2 Fusion Board

The goal of an image fusion processor is to gather the input signals and to fuse the signals into a single output using a specific algorithm. Some image fusion processors allow the user to manipulate the algorithm while other processors prevent the manipulation of the algorithm. For the purpose on an open source desk top application it is recommended that an image fusion processor be selected that can support several inputs, as well as, providing the capability of utilizing multiple algorithms. The Octec ADEPT60 is an image fusion processor that meets these demands and is recommended.

6.3 Fusion Algorithms

Image fusion algorithms are critical to the image fusion process. They range from Multi-Scale Decomposition techniques which break down the input images into lower resolution and lower spatial density images before selecting the appropriate characteristics from each input image that are used for the fused image. There are also Non Multi-Scale Decomposition techniques that utilize statistical, numerical, and artificial neural networks theories to fuse images from different sources.

According to the literature reviewed the Shift-invariant Discrete Wavelet Transform receives the most favourable results in both subjective and objective measures for night vision imagery. The Laplacian pyramid scheme also receives favourable results. Due to the inconsistency in results present in the literature it is difficult to elect one algorithm as the best. Depending on the measure used to evaluate the algorithm it can lead to a discrepancy in the results. Therefore, it is important to evaluate all the algorithms for each individual

6.4 Evaluation Metrics

The fusion test bed will be used to collect video for post-hoc psychophysical testing (subjective). Overall the correlation between subjective results and statistical based objective performance measures identified in the literature was poor. Recent developments in metrics based upon perception-information models have shown promise. The improved correlation between subjective and objective results for the feature and information-based metrics suggests that the following objective metric should be included in the fusion test bed analysis system.

- Edge Dependent Fusion Quality Index (QE);
- Fusion Quality Measure/Index (Q);
- Weighted Fusion Quality Index (QW);
- Universal Image Quality Index (UIQI); and
- Visual Difference (VDA.

6.5 Fusion Test Bed System Overview

The knowledge gained from the literature review will help support the Vision SST fusion test bed development. Lessons learned have been captured and are summarized below to support the fusion test bed development. It should be noted that the current vision of the fusion test bed is to capture real time digital video images for post-hoc fusion assessment. The system will utilize mains power and will be field portable but not ruggedized. The system will require a sensor pod containing multispectral sensors with a mounting system and a processing pod. Please see Figure 42 for an example of the sensor pod used by Hines et al. (2005) for their Enhanced Vision System (EVS) using the Retinex digital image enhancement algorithm.

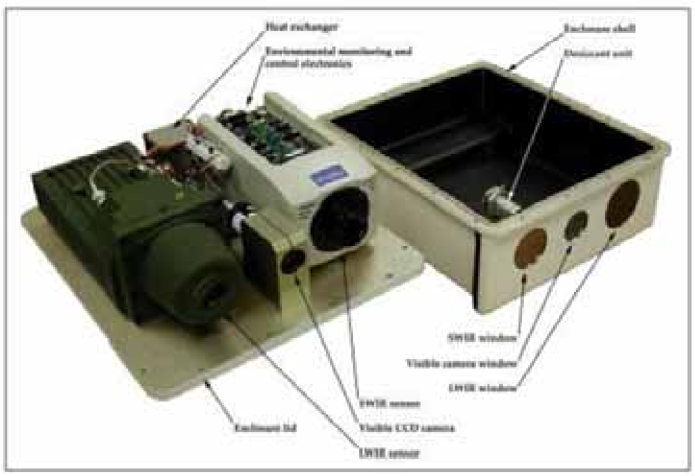

Figure 42: Imaging pod from Hines et al. 2005

The sensor pod could be physically separated from the processing pod. Fibre optic cables could be used to distribute video information to the processing pod which could be rack mounted.

The test bed could include the following subsystems:

- Sensors. The fusion test bed will include up to four sensors operating in LWIR, SWIR, NIR and visible bands. The identification of which sensors recommended are detailed in the following section.
- Imaging pod (camera rig). System to align multiple sensors as closely as possible. Initial requirements are detailed in a following section.
- Image capture system. Digital images will be captured in real time (at a minimum of 30Hz). Feeds to fusion board/ frame grabber/ the Digital Signal Process Board (DSP) will be via cable.
- Image registration system. The digital image sources must be accurately registered for optimum fusion performance. While some fusion boards will do this automatically other approaches require registration marks.
- Image processing system. Raw images may need pre-fusion processing to optimize fusion performance.
- Fusion kernal. Source images will be fused using selectable algorithms. Fusion kernel to also output selected objective fusion metric scores.
- User graphical interface system
- Image storage system

- Power system
- Display system

Mutispectral Imaging Sensors:

The test bed should be able to collect real time digital video from up to four sensors simultaneously. The sensors/cameras could be any of the following:

- Day camera;
- Night camera – either a LLLTV, I^2CMOS sensor or EBAPS sensor;
- NIR/SWIR sensor;
- MWIR (note MWIR was not utilized in man portable systems); and
- LWIR sensor.

Mounting Pod:

A mechanism to mount up to four sensors will be required. The sensors will be mounted in a side by side stacked configuration to reduce parallax errors (minimum offset as possible). A mechanism to precisely set the elevation (pitch), roll, and yaw of each sensor will be required. Additionally the sensors should be mounted on a mechanism that will allow for quick and easy orientation changes. The mounting pod should be able to attach to a tripod for gross adjustments.

- The mounting pod must be able to permit the sensors to be co-aligned or bore sighted; and
- While every effort will be made to select high performance but miniaturized sensors, COTS systems may be relatively large. One approach to co-align sensors is to utilize dichroic beam splitters – see Figure 43.

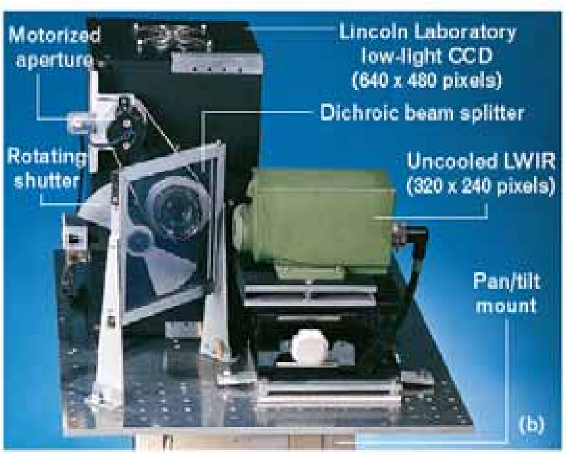

Figure 43: Dichroic beam splitter to co-align two sensors-from Waxman et al (1998)

Image Registration System

An image registration system is required to remove lens distortion errors and to remove bore-sighting inaccuracies. Some fusion boards will utilize their own registration algorithms based on image contours. Other systems require manual image registration.

- Propose we utilize registration markers in the scenes for continuous registration. May be able to simply register the sensors at the start of the data collection period and at the beginning of the session;

- Utilize contour based registration algorithm or multifactor registration system to align sensors. The system would do the following image feed adjustments:
    - Scaling,
    - Translation,
    - Rotation, and
    - (Match images to a common grid):
- If we need to use different FOV sensors then we should utilize the lowest FOV as the baseline for registration. The higher FOV would be registered to the lowest using affine transforms;
- If possible use automatic mapping adjustment algorithms to re-register images periodically; and
- Optical differences between the different sensor lenses may cause minor differences in magnification between sensors at the edges. A distortion correction board should reduce these errors.

Image Processing System

While registered images will be collected by the fusion test bed, it is proposed that the fusion test bed be designed to permit real time image processing and fusion. Possible real time image processing to include:

- Contrast normalization;
- Adaptive histogram equalization;
- Adaptive – automatic gain and level functionality;
- Image enhancement;
- Radiometric transformation;
- Dynamic range compression;
- Colour consistency;
- Colour and lightness rendition;
- Noise filtering; and
- Intensity stretching, edge sharpening, haze removal, adaptive smoothing, isotropic smoothing

Image Fusion System

The fusion test bed will include a fusion kernel to implement selected fusion algorithms.

Imaging Fusion Module (Algorithms)

The fusion test bed should permit the use of different fusion approaches. Fusion algorithms selected for testing should include as a minimum the following:

- Shift-invariant Discrete Wavelet Transform; and
- The Laplacian pyramid scheme.

Fusion Assessment Module.

The fusion test bed should permit the evaluation of image fusion using a variety of objective metrics. Possible metrics to include:

- Universal Image quality Metric (UIQI);
- Edge Dependent Fusion Quality Index (QE);
- Fusion Quality Measure/Index (Q);

- Weighted Fusion Quality Index (QW);
- Universal Image Quality Index (UIQI); and
- Visual Difference (VDA).

Image Storage System

The test bed will require the capability to capture the following images and information:

- Raw sensor images;
- Fused images;
- Sensor setup and parameter adjustments; and
- Sensor registration.

Graphical User Interface

The fusion test bed will require a graphical user interface to permit the operator to perform the following functions:

- Raw image processing;
- Fusion algorithm selection and parameter adjustment;
- Parameter setting capture; and
- Image capture controls,

A number of commercial software modules are available to support image fusion. In addition to fusion tools a number of image processing tools and software programs are available. Indigo systems offers a number of radiometric software modules to acquire, radiometrically calibrate, analyze and document data from digital imaging systems.

Image storage system

The test bed will store the captured images on a suitable sized hard drive.

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					Performance Specifications											Sensor Specifications		Dimensions				
Ref #	Manufacturer	Product	Monochrome / Color	Imaging Technology	Horizontal Resolution (lines)	Vertical Resolution (lines)	Maximum Frame Rate (fps)	At least 640 x 480 and 30 fps	Shutter Speed (seconds)	Sensitivity (Lux)	Performance	Format / Output	Resolution	Lens Mount	Shutter Control	Quantum Efficiency (%)	Fill Factor (%)	Width / Diameter (inch)	Height (inch)	Length (inch)	Weight (lb, oz)	Notes
A1-1	DVC	DVC-1412 Series -- DVC-1412AM-MS	Monochrome	CCD	1392	1040	100	No	9.30E-5 to 0.0980	0.2368	High Speed, Gain Control, Cooled*	RS644 / LVDS, FireWire, CameraLink	12 bits	C-Mount	Electronic Shutter	62	100	3.26	4.47	1.89	1, 2	Fast readout, low noise, high signal to noise ratio, asynchronous reset
A1-2	DVC	DVC-1412 Series -- DVC-1412AM-MT	Monochrome	CCD	1392	1040	100	No	9.30E-5 to 0.0980	0.2368	High Speed, Gain Control, Cooled*	RS644 / LVDS, FireWire, CameraLink	12 bits	C-Mount	Electronic Shutter	62	100	3.9	4.79	2.72	1, 2	Fast readout, low noise, high signal to noise ratio, w/ cooler
A1-3	DVC	DVC-1412 Series -- DVC-1412AC-00	Color	CCD	1392	1040	100	No	9.30E-5 to 0.0980	0.7535	High Speed, Gain Control	RS644 / LVDS, FireWire, CameraLink	12 bits	C-Mount	Electronic Shutter	62	100	3.25	3.25	1.73	1, 2	Fast readout, low noise, high signal to noise ratio, asynchronous reset
A1-4	DVC	DVC-1412 Series -- DVC-1412AC-TE	Color	CCD	1392	1040	100	No	9.30E-5 to 0.0980	0.7535	High Speed, Gain Control, Cooled	RS644 / LVDS, FireWire, CameraLink	12 bits	C-Mount	Electronic Shutter	62	100	3.9	3.9	2.57	1, 2	Fast readout, low noise, high signal to noise ratio, asynchronous reset
A1-5	Intevac	E2006 Low Light Level Camera			1280	1024	30	Yes		0.00001		RS-232	10 bits	C-Mount				2	2	3	0, 8.4	Camera functions include non-uniformity correction, histogram equalization, horizontal image orientation
A1-6	NAC Image Technology	HSV High-Speed Color Video System -- HSV-500C3	Color	CCD	510	485	500	No	1.00E-4 to 0.0020	2500	High Speed	NTSC, RS232	24	Bayonet	Electronic Shutter, External Trigger			2.99	3.03	5.59	2, 0	Ideal for military testing and monitoring, and biomechanical applications
A1-7	NAC Image Technology	Memrecam fx -- RX5 Micro Camera Head	Monochrome, Color	CCD	1280	1024	10000	Yes	? to 1.00E-6	5000	High Speed	Ethernet, Fibre Channel, VGA	10 bits	F-Mount, NF	Electronic Shutter, External Trigger			0.827	0.827	3.9	0, 9.6	Single or multi-camera head high speed color video system
A1-8	PCO Imaging	PCO Series -- Model PCO.1600	Monochrome, Color	CCD	1600	1200	30	No	5.00E-7 to 4.23E6		Cooled, Anti-Blooming	FireWire, CameraLink	14 bits	C-Mount, F-Mount	Electronic Shutter	55		3.31	2.6	6.89	4, 0	Image sensor cooled thermoelectrically, integrated image memory
A1-9	PCO Imaging	PCO Series -- Model PCO.2000	Monochrome, Color	CCD	2048	2048	14.7	No	5.00E-7 to 4.23E6		Cooled, Anti-Blooming	FireWire, CameraLink	14 bits	C-Mount, F-Mount	Electronic Shutter	55		3.31	2.6	6.89	4, 0	Image sensor cooled thermoelectrically, integrated image memory
A1-10	PCO Imaging	PCO Series -- Model PCO.4000	Monochrome, Color	CCD	4008	2672	5	No	5.00E-6 to 4.23E6		Cooled, Anti-Blooming	FireWire, CameraLink	14 bits	C-Mount, F-Mount	Electronic Shutter	50		3.31	2.6	6.89	4, 3	Image sensor cooled thermoelectrically, integrated image memory
A1-11	PCO Imaging	Pixelfly Series -- Model Pixelfly	Monochrome, Color	CCD	640	480	50 / 95 / 177	Yes	5.00E-6 to 65.00		Anti-Blooming	RS644 / LVDS, Ethernet, RJ45 Connector	12 bits	C-Mount	Electronic Shutter	43		1.54	1.54	2.68	0, 8.8	Has digital temperature compensation instead of thermo-electrical cooling
A1-12	PCO Imaging	Pixelfly Series -- Model Pixelfly QE	Monochrome, Color	CCD	1392	1024	23	No	5.00E-6 to 65.00		Anti-Blooming	RS644 / LVDS, Ethernet, RJ45 Connector	12 bits	C-Mount	Electronic Shutter	62		1.54	1.54	2.68	0, 8.8	Has digital temperature compensation instead of thermo-electrical cooling
A1-13	PCO Imaging	Sensicam Series -- Model Sensicam EM	Monochrome, Color	CCD, emCCD	1004	1002	13	No	7.50E-5 to 3600		Cooled, Anti-Blooming	Serial	12 bits	C-Mount, F-Mount	Electronic Shutter	65		3.66	3.07	8.27	3, 8	Image sensor cooled thermoelectrically, used for night vision applications
A1-14	PCO Imaging	Sensicam Series -- Model Sensicam QE	Monochrome, Color	CCD	1374	1040	19.8	No	5.00E-7 to 1000		Cooled, Anti-Blooming	Serial	12 bits	C-Mount	Electronic Shutter	62		3.66	3.07	8.27	3, 8	Image sensor cooled thermoelectrically, used for fluorescence imaging
A1-15	PCO Imaging	Sensicam Series -- Model Sensicam QE Double Shutter	Monochrome, Color	CCD	1376	1040	19.8	No	5.00E-7 to 3600		Cooled, Anti-Blooming	Serial	12 bits	C-Mount	Electronic Shutter	62		3.66	3.07	8.27	3, 8	Image sensor cooled thermoelectrically, high spectral sensitivity

						Performance Specifications												Dimensions					
Ref #	Manufacturer	Product	Monochrome / Color	Specialty Camera Type	Application / Industry	Horizontal Resolution (lines)	Vertical Resolution (lines)	Maximum Frame Rate (fps)	At least 640 x 480 and 30 fps	Shutter Speed (seconds)	Sensitivity (Lux)	Performance	Format / Output	Resolution	Lens Mount	Shutter Control	Quantum Efficiency (%)	Width / Diameter (inch)	Height (inch)	Length (inch)	Weight (oz)	Operating Temperature (F)	Notes
A2-1	Intevac	NightVista E2010			Surveillance applications	1280	1024	30	Yes		10-4 to 10+4			10 bits	C-Mount			2	2	3	8		CMOS-based day.night video camera may be used for day or night surveillance
A2-2	Intevac	NightVista E3010		plug and play	Surveillance applications	1280	1024	30	Yes			Progressive scan											"plug and play" digital image intensifier (DI2) module specifically designed for integration into imaging systems such as head/helmet-mounted displays, rifle sights and small EO/IR surveillance gimbals.
A2-3	Irvine Sensors Corp.	MVC-FF0229	Monochrome		Industrial, Security, Traffic Control, Other	752	480	60	Yes					10 bits		Electronic global		0.627	1.34	1.4		40.00 to 185	High speed, low noise, global shuttered. Byte-wide output.
A2-4	PCO Imaging	PCO Series -- Model PCO.1200 HS	Monochrome, Color	High Speed	Broadcast, Industrial, Scientific, Other, High Speed Particle Image Velocimetry	1280	1024	1357	Yes	5.00E-8 to 5.00		Anti-Blooming	FireWire, CameraLink	10 bits	C-Mount, F-Mount	Electronic Shutter	27	3.31	2.6	6.89		41.00 to 104	High speed, low noise, has fast image recording with 1 GB per second
A2-5	PCO Imaging	PCO Series -- Model PCO.1200 S	Monochrome, Color	High Speed	Broadcast, Industrial, Scientific, Other, Hydrodynamics, Fuel Injection	1280	1024	1068	Yes	1.00E-6 to 1.0000		Anti-Blooming	Ethernet, FireWire, CameraLink	10 bits	C-Mount, F-Mount	Electronic Shutter	25	3.31	2.6	6.89		41.00 to 104	High speed,, has fast image recording with 1 GB per second
A2-6	Prosilica Inc.	GE640C -- 02-2001A	Color	High Speed, Vision Sensor	Industrial, Security	659	493	200	Yes	2.00E-5 to 5.00		Progressive Scan, Gamma Correction, Gain Control, Anti-Blooming	Ethernet	10 bits	C-Mount, CS-Mount*	Electronic Shutter, External Trigger		2	1.5	2.46		? to 122	GigE Vision, gigabit Ethernet, high speed, global shutter, VGA
A2-7	Vision Research Inc	High Speed Camera -- Phantom® v6.2	Monochrome, Color	High Speed		512	512	1400	No	5.00E-6 to 1.00E-5	1200		NTSC, PAL, RS232, Ethernet, SDI	8 bits, 24	C-Mount	External Trigger		3	3	2			Multi-head high speed digital imaging system

Ref #	Manufacturer	Product	Length (inch)	Width / Diameter (inch)	Height (inch)	FOV (degrees)	Weight (lbs, oz)	Detector resolution (pixels)	Video refresh rate (Hz)	At least 640 x 480 and 30 fps	Pitch (micron)	Detector Type	Thermal sensitivity (mK)	Spectral Response (microns)	Notes
A3-1	FLIR	SC4000 HS-NIR/ SC6000 HS-NIR				depends on lens: range 5.5 x 4.4 to 63.2 x 52.4		320 x 256 / 640 x 512	programmable 1-420/ 1- 126	Yes		Indium Gallium Arsenide (InGaAs)		0.9 -1.7	New standard for military themal imaging. Available in various wavebands across the spectrum.
A3-2	Intevac	LIVAR 400 Short Wave Infrared Camera	2.5	2.58	2.8			640 x 480	upto 28.5	Yes		EBCMOS		0.95 - 1.55	Long range target identification for airborne, ground, marintime and dismounted platforms beyond 20 km). Compliments cooled and uncooled FLIR detection devices and provides long range high resolougtion target ID. Perfect for covert operators and compact systems.
A3-3	Sensors Unlimited Inc (Goodrich)	SU640SDV-1.7 RT SU640SDV Vis-1.7 RT High Resolution InGaAs and Vis-InGaAs SWIR Area Cameras	6.22	3	3		~2, 6	640 x 512	30	Yes	25	InGaAs, CMOS readout		0.4 - 1.7 or 0.9 - 1.7	
A3-4	Sensors Unlimited Inc (Goodrich)	SU640SDWH-1.7 RT SU640SDWHVIS-1.7 RT High Resolution Windowing InGaAs and Vis-InGaAs SWIR Area Cameras	6.22	3	3		~2, 6	640 x 512	109	Yes	25	InGaAs		0.4 - 1.7 or 0.9 - 1.7	
A3-5	Sensors Unlimited Inc (Goodrich)	SU320KTX-1.7RT High Sensitivity InGaAs SWIR Camera	1.64	1.5	1.5		~3, 2	320 x 240	60	No	40	InGaAs		0.9 - 1.7	
A3-6	Sensors Unlimited Inc (Goodrich)	SU320M-1.7RT InGaAs SWIR Camera	1.96	2.36	3.74		<11oz	320 x 240	50 - 60	No	40	InGaAs		0.9 - 1.7	
A3-7	Sensors Unlimited Inc (Goodrich)	SU320MX-1.7RT High Sensitivity InGaAs NIR MiniCamera	1.96	2.36	3.74		<11oz	320 x 240	25 -30	No	40	InGaAs		0.9 - 1.7	
A3-8	Sensors Unlimited Inc (Goodrich)	SU320MVis-1.7RT Visible and SWIR Response InGaAs NIR MiniCamera	1.96	2.36	3.74		<11oz	320 x 240	50 -60	No	40	InGaAs		0.4 - 1.7	
A3-9	Sensors Unlimited Inc (Goodrich)	SU320MSVis-1.7RT Visible and SWIR Response InGaAs MiniCamera	1.96	2.36	3.74		<11oz	320 x 256	25 -30	No	25	InGaAs		0.4 - 1.7	
A3-10	Lumitron	NIR320 OEM InGaAs Near-Infrared Camera	5.25	3	3	depends on lens: range 3.9 x 3.1 to 21 x 16.8	2, 8	320 x 256	60	No	30	InGaAs		0.9 - 1.7	

Ref #	Manufacturer	Product	Length (inch)	Width / Diameter (inch)	Height (inch)	FOV (degrees)	Weight (lbs, oz)	Detector resolution (pixels)	Video refresh rate (Hz)	At least 640 x 480 and 30 fps	Pitch (micron)	Detector Type	Thermal sensitivity (mK)	Spectral Response (microns)	Display polarity	Time to operation (seconds)	Power source	Operating time (hours)	Detection Range (metres)	Diopter Adjustment (diopters)	Interpupillary Adjustment (mm)	System Magnification
A4-1	DRS NVEC	UTWS (Urban Thermal Weapon Sight II)	12.1	2.6	3.8	18 x 13.5	2	320 x 240	60	No	25	Vox microbolometer	<50	8 - 12 (LWIR)	black hot/ white hot gray scale, green scale, red scale	4 typical	4 AA batteries	10	550			
A4-2	DRS NVEC	CSTWS (Crew Served Thermal Weapon Sight II)	16	4.25	5.5	9 x 6.9 (e-zoom 3 x 2.3)	4, 2	640 x 480	30	Yes	25	Vox microbolometer	<50	8 - 12 (LWIR)	black hot/ white hot gray scale, green scale, red scale	4	6 AA batteries	18	2200			
A4-3	DRS NVEC	MX-2 (Rugged miniature thermal imager)	8.5	5.5	3	18 x 13.5	2, 13	320 x 240	60	No	28	Vox microbolometer	<70	8 - 12 (LWIR)	white-hot/ black-hot	<12	cassette of 6 AA batteries	7.5	530			
A4-4	DRS NVEC	COBRA-IR (Covert Over Barrier Recon Assistant - Infrared)	2.5	4	9.5	36 x 27	1, 14	320 x 240	30	No	38	Vox microbolometer	=80	8 - 12 (LWIR)	white-hot	<3 typical	3 AA batteries	>4	up to 500			
A4-5	DRS NVEC	HelmetIR	3	3	3	17 x 12	1, 3	160 x 120	20	No	47	Amorphous silicon microbolometer	=100	8 - 12 (LWIR)	white-hot	5 typical	2 AA batteries	7+	320			
A4-6	DRS NVEC	Mini-IR Plus (hand-held thermal imager)	5.25	4.5	2	11 x 8		160 x 120	30	No	30	Amorphous silicon microbolometer	=60	8 - 12 (LWIR)	white-hot	<5 typical	2 AA batteries	=4	upto 450			
A4-7	DRS NVEC	PVS-7 Style (Single tube NVG)	6	8.25	3.5	40											2 AA batteries	55		-6 to +2	15	1x (3x with afocal lens)
A4-8	DRS NVEC	MANTIS (Multi-Adaptable Night Tactical Imaging System)	3	2	2.5		15.8 oz										2 AA batteries	40-60		-6 to +2		1x
A4-9	DRS NVEC	4x Raptor (4-power night vision weapon sight)	12	3.75	3.5	8.3	3, 6										2 AA batteries	40		-5 to + 2	30	4x
A4-10	DRS NVEC	6x Raptor (6-power night vision weapon sight)	14	4.5	4.5	5.7	5, 8										2 AA batteries	40		-5 to + 2	30	6x
A4-11	ELCAN (Raytheon)	SpecterIR+				9 x 7	< 3, 0	320 x 240						8 -12 (LWIR)			3 AA batteries	> 4	750			2x
A4-12	FLIR	ThermoVision Photon	2.1	2	1.8	47 x 35	~4oz	320 x 240				microbolometer		7.5 - 13.5 (LWIR)								2x
A4-13	FLIR	ThermoVision ThermoSight	10			15.5 x 9.9	~ 1, 3							7.5 - 13.5 (LWIR)			4 AA batteries	2.5 - 7				
A4-14	FLIR	ThermoVision A10	1.45	1.35	1.45			160 x 120				Uncooled microbolometer		7.5 - 13.5 (LWIR)		2 max						
A4-15	FLIR	SC4000 HS MWIR/ SC6000 HS-MWIR				depends on lens: range 11 x 9 to 62 x 51		320 x 256 / 640 x 512	programmable 1-420/ 1- 126	Yes	25	Indium Antimonide (InSb)	<25 (18 typical)	3.0 -5.0 (MWIR)								
A4-16	FLIR	SC4000 HS LWIR/ SC6000 HS-LWIR				depends on lens: range 5.5 x 4.4 to 63.2 x 52.4		320 x 256 / 640 x 512	programmable 1-420/ 1- 127	Yes	25	Gallium Arsenide (GaAs) QWIP	< 35	8.0 -9.2 (LWIR)								
A4-17	Irvine Sensors	Personal Miniature Thermal Viewer	4	1.8	3	20 or 40	< 12 oz	320 x 240	60	No			<50	LWIR		<0.4 sec	2 AA batteries	>5				
A4-18	Irvine Sensors	CAM-NOIR Thermal Camera						320 x 240		No												
A4-19	Irvine Sensors	Miniature Camera						from 320 x 240 to 1280 x 1024									4 AA batteries					
A4-20	L3 Communications Thermal-Eye	X200xp	5.25	4.5	2	11 x8	13 oz	160 x 120	30	No	30	amorphous silicon microbolometer	=50	7 -14 (LWIR)	white =hot, black= cold	~3	2 AA batteries	2 - 6	450			
A4-21	L3 Communications Thermal-Eye	3600AS	1.79	1 - 1.3	2.5	50 x 37	2.38	160 x 120	30	No	30	amorphous silicon microbolometer	<50	7 -14 (LWIR)		~2.4						
A4-22	L3 Communications Thermal-Eye	3620AS	1.79	1 - 1.3	2.5	11 x 8, 17 x12, or 32 x24	2.38	160 x 120	30	No	30	amorphous silicon microbolometer	<50	7 -14 (LWIR)		~2.4						
A4-23	L3 Communications Thermal-Eye	3640AS	1.79	1 - 1.3	2.5	25 x 18	2.38	160 x 120	30	No	30	amorphous silicon microbolometer	<50	7 -14 (LWIR)		~2.4						
A4-24	Lumitron	UC320U OEM Microbolometer Infrared Camera	5.5	3	3	4.1 x 3.2 to 25 x 19	2, 0	320 x 240	60	No	35	microbolometer	<60	8 -14 (LWIR)								
A4-25	Lumitron	UC320D OEM Microbolometer Infrared Camera	7	3	3	4.5 x 3.5 to 69 x 53	2, 0	320 x 240	60	No	51	microbolometer	<60	8 -14 (LWIR)								

Ref #	Manufacturer	Product	Notes
A4-1	DRS NVEC	UTWS (Urban Thermal Weapon Sight II)	Used fo day/night reconnaissance, surveillance and target acquisition for individual and crew weapons. The narrow FOV is designed for distance target detection and recognition. Lightweight (2 lbs).
A4-2	DRS NVEC	CSTWS (Crew Served Thermal Weapon Sight II)	Used fo day/night reconnaissance, surveillance and target acquisition for individual and crew weapons. 3 x digital zoom.
A4-3	DRS NVEC	MX-2 (Rugged miniature thermal imager)	High performance multipurpose, tactical hand-held thermal imager, tripod, or weapon mounted employement. Removeable eyepiece for remote display (helmet) mountable.
A4-4	DRS NVEC	COBRA-IR (Covert Over Barrier Recon Assistant - Infrared)	Compact tactical thermal and video periscope. Can be used as a hand-held or tripod-mounted covert camera system.
A4-5	DRS NVEC	HelmetIR	This thermal imager can see in total darkness, through battlefield obscurants and foliage. Flexible monocluar eyepiece with flip-up capability.
A4-6	DRS NVEC	Mini-IR Plus (hand-held thermal imager)	Small enough to store in BDU pocket.
A4-7	DRS NVEC	PVS-7 Style (Single tube NVG)	Designed for US ground forces. Veratile system that delivers exceptional gain and resolution on the darkets nights. Quick release for one hand mounting.
A4-8	DRS NVEC	MANTIS (Multi-Adaptable Night Tactical Imaging System)	Can be hand-held for direct observation or weapon mounted for accurate night targeting.
A4-9	DRS NVEC	4x Raptor (4-power night vision weapon sight)	Is the most accurate night imaging device designed to meet military requirements for long range accuracy.
A4-10	DRS NVEC	6x Raptor (6-power night vision weapon sight)	Is the most accurate night imaging device designed to meet military requirements for long range accuracy.
A4-11	ELCAN (Raytheon)	SpecterIR+	Lightweight, rugged, thermal weapon sight. Operational in sand, smoke, fog. Uncooled detector technology.
A4-12	FLIR	ThermoVision Photon	Long wave TI get clear imagery in total darkness, through smoke, fog, and most obscurants
A4-13	FLIR	ThermoVision ThermoSight	Long wave TI, can be used as hand held for scouting, survellance, and covert operations, small and lightweight, electronic bore sighting
A4-14	FLIR	ThermoVision A10	World's smalledst infrared camera, high sensitivity to detection, modular, highly flexible architecture supports a wide range of features, options and accessories.
A4-15	FLIR	SC4000 HS MWIR/ SC6000 HS-MWIR	New standard for military themal imaging. Available in various wavebands across the spectrum.
A4-16	FLIR	SC4000 HS LWIR/ SC6000 HS-LWIR	New standard for military themal imaging. Available in various wavebands across the spectrum.
A4-17	Irvine Sensors	Personal Miniature Thermal Viewer	Unique shutterless deisng, custom optical, image processing packaging and interface options available
A4-18	Irvine Sensors	CAM-NOIR Thermal Camera	Can operate over a broad temperature range without the need for temp stabilzation. "Instant on" capability.
A4-19	Irvine Sensors	Miniature Camera	IR or RF control and data links. Remote shitter trigger input. Interchangeable lens system
A4-20	L3 Communications Thermal-Eye	X200xp	For target detection, force protection, routine patrols, search and rescue, distibuted surface/IED detection, covert surveillance, and fugitive pursuit.
A4-21	L3 Communications Thermal-Eye	3600AS	Small size and best-in-class power consumption, open architecture (easy access to video processing chain with sophisticated GUI)
A4-22	L3 Communications Thermal-Eye	3620AS	Small size and best-in-class power consumption, open architecture (easy access to video processing chain with sophisticated GUI)
A4-23	L3 Communications Thermal-Eye	3640AS	Small size and best-in-class power consumption, open architecture (easy access to video processing chain with sophisticated GUI)
A4-24	Lumitron	UC320U OEM Microbolometer Infrared Camera	
A4-25	Lumitron	UC320D OEM Microbolometer Infrared Camera	

Ref #	Manufacturer	Product	Detector resolution (pixels)	Pixel size (microns)	Detector Type	Spectral Response (microns)	Video refresh rate (Hz)	Video Output	At least 640 x 480 and 30 fps	Dimensions Width (inch)	Height (inch)	Length (inch)	Notes
A5-1	Intevac	NightVista	640 x 480	12 x 12	GaAs	5- 9	30	RS-170 or interlaced digital video	Yes				Developed for commercial security camera applications. Incorporates non-uniformilty correction, bad pixel replacement, and histogram equalization image processing functions.
A5-2	Intevac	ISIE6	1280 x 1024	6.7 x 6.7	GaAs	5- 9	~27.5	10 bit digital output, progressive scan	Yes				
A5-3	Intevac	ISIE10	1280 x 1024	10.8 x 10.8	GaAs	5- 9	37	10 bit digital output, progressive scan	Yes				In development stages.

Annex B: Image Sensor Fusion Boards

Fusion Hardware	Size	Weight	Chip or board	# of inputs	Processing speed	Open arch	Real-time	Power
Equinox DVP-4000	3” x 3”	2 oz	Chip	2	60 fps		YES	1.5 W Consumption
Imagize FP-3500	1.4” x1.4”x 0.5”	0.75 oz	2 board system	2	30 fps, 60 fields/s		YES	0.6 W- 30 fps 0.9 W- 60 fps
Irvine VIP/Balboa			20 Processors		40 MHz			
EPIX PIXCI-D2X	4.913” x 4.2”							3.3 V or 5 V PCI Signaling
Octec ADEPT60	233.4mm x 160mm		Board	2 Video Inputs			YES	5 V
Acadia I PCI Vision Board			Single Chip	2	30 fps, 60 field/s		YES	15 W
VMETRO PMC-FPGA03				2				

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(U) The major objectives of the report were to identify and review the field of image fusion and contributing technologies and to recommend systems, algorithms and metrics for the proposed SIHS TD Vision SST fusion test bed. A search of the relevant literature was conducted using the relevant databases and approximately 150 papers of primary utility were identified for review. The report provides an in−depth introduction to fusion hardware and software technologies and evaluation metrics. The effort focused on identifying promising sensing fusion technologies that could be utilized by the Soldier's Integrated Helmet System Technology Demonstrator (SIHS TD).

The SIHS TD Vision Sub−System Team plans to develop a fusion test bed in the near term to quantify dismounted soldier performance. The systems examined in this project were projected to be mature and compatible with man packed applications by the year 2007. The literature review identified considerable technological advancements in sensor size reduction, power demand reductions, and increases in resolution. The report analyzed select sensor systems for their suitability in the fusion test bed based on sensor form factors, detector resolution, and real time performance. Recommendations on what sensors to include in the fusion test bed are included. The report provides an in−depth introduction into image fusion approaches. A list of potential fusion algorithms were identified and reviewed. Recommendations on what fusion algorithms should be examined in the fusion test bed are provided. A number of subjective and objective fusion evaluation approaches and metrics were proposed in the literature to quantify and qualify image fusion performance. Recommendations on what valid fusion metrics should be utilized in the fusion test bed are provided. Improvements to fusion subjective evaluation approaches are also detailed. Finally, summary suggestions for the Vision SST fusion test bed are provided.

(U) Le rapport a principalement pour objectifs de déterminer et d'examiner le domaine de la fusion d'images et des technologies d'appui, ainsi que de recommander des systèmes, des algorithmes et des mesures pour le banc d'essai de fusion de l'équipe des sous−systèmes de vision, dans le cadre de la démonstration de technologie − casque intégré pour soldat (DT − SIHS). Une recherche de la documentation pertinente effectuée dans les bases de données appropriées a permis de trouver environ 150 documents d'utilité immédiate pour l'examen. Le rapport présente en détail les technologies et les mesures d'évaluation du matériel et du logiciel de fusion. Les travaux visent essentiellement à déterminer les technologies prometteuses de fusion et détection, qui pourraient être utilisées dans le cadre de la DT − SIHS.

L'équipe des sous−systèmes de vision de la DT − SIHS planifie le développement à court terme d'un banc d'essai de fusion permettant de quantifier le rendement des soldats débarqués. Les systèmes examinés dans le cadre de ce projet devraient être au point et compatibles avec les applications portatives d'ici 2007. L'examen de la documentation a fait ressortir des progrès technologiques considérables en matière de réduction de la taille des capteurs, de réduction de la puissance consommée et d'augmentation de la résolution. Le rapport analyse des systèmes de capteurs sélectionnés pour établir leur adaptabilité au banc d'essai de fusion en fonction des facteurs de forme des capteurs, de la résolution des détecteurs et du rendement en temps réel. Des recommandations sont incluses quant aux capteurs à intégrer au banc d'essai de fusion. Le rapport présente en détail des méthodes de fusion d’images. Une liste des algorithmes de fusion possibles est dressée et examinée. Des recommandations portent sur les algorithmes de fusion qu’il y a lieu d’examiner pour le banc d’essai de fusion. Un certain nombre de méthodes et de mesures d’évaluation subjective et objective de la fusion sont proposées dans la documentation en vue de la quantification et de la qualification du rendement de fusion d’images. Des mesures de fusion valides sont recommandées pour le banc d’essai de fusion. Des détails sont également fournis sur les améliorations qu’il y a lieu d’apporter aux méthodes d’évaluation subjective de la fusion. Enfin, des suggestions sommaires sont présentées pour le banc d’essai de fusion de l’équipe des sous−systèmes de vision.

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(U) SIHS; Soldier Integrated Headwear System; fusion systems; image fusion; fusion hardware; sensors; sensor systems; detection